University of Alberta

Runoff Generation on Reclaimed Watersheds

by

Theodore Edward Harms ©

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of Master of Science

in

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ABSTRACT

Surface runoff from summer rainfall and snowmelt was monitored for two reclaimed surface-mined watersheds at both the hillslope microframe and watershed scales from fall 1992 until fall 1995 to: compare watershed and hillslope surface runoff volume and watershed peak flows; identify the major flow processes occurring at the watershed scale; compare the runoff coefficients at the hillslope to the watershed scale and determine the variability of hillslope snowmelt runoff, infiltration and evaporation. Snowmelt runoff accounted for over 85% of annual runoff in two of three years. The highest peak flow of 79 L s^{-1} occurred during a summer rainfall event. The dominant flow paths were infiltration-excess overland flow for one watershed and saturation overland flow for the other. Watershed runoff coefficients calculated from microframe runoff were consistently higher than runoff coefficients calculated from watershed runoff. Aspect was an important factor during snowmelt in determining the amount of evaporation, infiltration and subsequent surface runoff.

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1. BACKGROUND

1.1. Surface Mining: an Overview

Surface mining is the most widely used technique in Alberta for uncovering buried coal reserves. Thirty-one permitted surface mines were in operation in Alberta in 1992, with 69% of the province's electrical power requirement supplied from four of these mines (ERCB, 1993). Surface mining removes and handles large amounts of soil and overburden material to expose the buried coal. Many of the topographic, pedologic, geologic, hydrologic and vegetative features that existed prior to mining are modified as a result of the major surface disturbance.

Surface mining consists of three phases: exposure, active mining and rebuilding. The initial phase removes vegetation, strips and stockpiles topsoil and suitable subsoil material and removes the overburden (spoil) material that overlies the coal seams. The active mining phase removes the coal seam/seams. The final phase recontours, reconstructs soil profiles and revegetates the reclaimed area.

Topsoil and suitable subsoil are stripped and either stockpiled or spread immediately over a recontoured area ready for soil profile reconstruction. Once the soil is salvaged, the overburden is removed with a dragline (Hastie, 1991).

The overburden lithological sequence is inverted as it is removed by the dragline. The material that was near the surface becomes the material near the bottom of the disturbed overburden, and the material immediately above the coal seam becomes near surface material. The overburden material is left as it is dumped by the dragline until a sufficient amount has accumulated to recontour. Bulldozers are used to smooth and contour the spoil material to create the desired final topography.

The next phase is reconstruction of the soil profile. Stockpiled subsoil is spread over the recontoured spoil material in depths depending on the presence or absence of adverse chemical properties of the spoil material (Oddie and Bailey, 1988). Topsoil is finally spread over the subsoil material and vegetation is re-established.

Reclaimed fields are often seeded to perennial forage mix of grasses and legumes. A cover crop of an annual grain is often companion seeded the first year after reconstruction of the soil profile.

A major task for mine operators is not only to restore productive use once mining is complete, but also to minimize any adverse impact the mining operation may have on the surrounding areas. Surface runoff and subsequent erosion are directly altered by the mining process.

1.2. Research Justification

TransAlta Utilities Corporation operates the largest surface coal mine in Canada at the Highvale Mine 80 km west of Edmonton, Alberta, adjacent to Lake Wabamun. At present, TransAlta Utilities is not allowed to discharge any surface runoff originating within the mine boundary into Lake Wabamun. Consequently, surface runoff discharged from the reclaimed fields is not separated from surface runoff generated from other areas within the mine boundary (pits, haul roads, spoil piles, etc.). All surface runoff is directed by ditches either directly to a cooling pond, or to collection ponds and then pumped to the cooling pond. Water either to or from the cooling pond is exchanged with the North Saskatchewan River, 10 km away. Current regulations for maximum concentration of suspended solids in the discharge waters from the Sundance Plant cooling pond to the North Saskatchewan River is set at 50 ppm (Alberta Environmental Protection, 1978). A study of water quality of surface runoff from various sources within the active mine area and outside the mine perimeter was completed in 1991 (Monenco Consultants, 1992). Surface water of the lowest quality was from the active pit areas, haul roads and mine spoil piles. No assessments of water quality from the relaimed fields were made.

The active mining zone is progressing southward and the contribution of runoff from the reclaimed area to total runoff is increasing. Costs for handling surface runoff increase proportionately as the mine area increases. If the quality of the surface runoff from the reclaimed fields is within the standards set for allowable discharge, then collection ponds and cooling ponds could be bypassed and the discharge waters could be directed into natural drainage ways that drain into Lake Wabamun, obviating the need for handling surface runoff from this source. This diversion would, however, necessitate the construction of a separate drainage system for the surface runoff from the reclaimed fields.

1.3. References

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2. LITERATURE REVIEW

2.1. Surface Runoff

Three flow paths by which precipitation can become surface runoff from a watershed are: overland flow, subsurface (macropore) flow and groundwater flow (Anderson and Burt, 1990). Dominant flow paths are determined by the interactions of local vegetation, soil, climate, topography and geology.

Overland flow, as first described by Horton in 1931 (Chorley, 1978) and referred to as infiltration-excess overland flow, occurs when the rate of the incoming precipitation exceeds the infiltration capacity of the soil, and during snowmelt when infiltration into the soil is reduced due to frozen soil conditions (Dunne, 1978). Infiltration-excess overland flow is the dominant flow path in many arid and semi-arid environments due to the presence of desert pavement (Abrahams et al., 1992) and in areas within a watershed where infiltration is restricted (Allan and Roulet, 1994).

Overland flow also occurs when the permanent watertable or a perched watertable intersects the soil surface and creates a saturated area that restricts infiltration. Incoming precipitation cannot infiltrate the saturated areas and hence becomes surface runoff. Overland flow occurring as a result of these saturated areas is referred to as saturation overland flow. In humid forested catchments, saturation overland flow has been identified as the most important flow process (Dunne and Black, 1970). Saturation overland flow has also been described for areas of convergent flow (hollows) within a catchment area (Anderson and Kneale, 1982; Burt and Butcher, 1985), and was identified as the dominant flow process occurring in groundwater discharge areas within a forested wetland site (Waddington et al., 1993).

Subsurface flow or interflow are terms used to describe the movement of water within a thin layer of soil mantle to the permanent or ephemeral stream channel. Flow within the soil mantle occurs on hillslopes when the surface horizon or horizons within a soil profile are underlain by a less permeable horizon or bedrock (Jamison and Peters, 1967; Renzetti et al., 1992). The soil hydraulic conductivity in the direction of the hillslope is greater than the hydraulic conductivity perpendicular to the hillslope and hence water moves downslope within the soil mantle (Ahuja and Ross, 1983). Subsurface flow becomes overland flow by intersecting a stream channel or by returning to the surface if the within-mantle downslope route is restricted by a subsurface outcropping or a saturated area (return flow). Compared to surface flow, subsurface storm flow generally takes longer to reach the channel bottom and the magnitude of the flow is reduced (Dunne and Black, 1970). Macropores at the soil surface and within the soil mantle increase the velocity and the quantity of flow via this route (Leaney et al., 1993).

Subsurface flow or interflow has been identified as the major runoff-generating mechanism occurring within some watersheds (Anderson and Burt, 1990). Contributions to watershed discharge via this route can be direct in that subsurface flow discharges via a seepage face into a channel or stream, or more importantly, subsurface flow can create expanded saturated areas along valleys and channels where saturation overland flow and return flow occur (Anderson and Burt, 1990).

Resultant hydrographs where infiltration overland flow is the dominant flow path display short lag times and times to peak, steep rising and recession limbs and high instantaneous peak discharge. Hydrographs for watersheds where saturation overland flow predominates are similar to infiltration-limited overland flow hydrographs when antecedent soil moisture conditions are high. When antecedent soil moisture conditions are low, there is a longer lag time and time to peak due to the delay as the contributing areas saturate. Subsurface stormflow hydrographs are generally of lower instantaneous peak intensity, the peak is delayed with longer lag times and the rising and recession limbs are gradual (Dunne, 1978).

Many or all of the flow mechanisms can exist in a heterogeneous landscape and "... the timing and shape of the watershed hydrograph is a composite of the dominance of the different flow pathways..." (Allan and Roulet, 1994).

2.2. Surface Runoff from Reclaimed Land

Final hillslope (length, steepness, shape) and watershed (size, shape, channel steepness, channel length, depressions) characteristics are established during the recontouring phase of reclamation. Many of the reclaimed watershed's topographic and soil profile features determine the dominant flow pathways, contributing areas for flow and total amount of surface runoff.

The dominant flow path from newly reclaimed surface mined watersheds is infiltration-limited overland flow (Guebert and Gardner, 1992; Ritter and Gardner, 1993). Infiltration rates into newly reconstructed soil profiles are often considerably lower than those of undisturbed areas (Guebert and Gardner, 1992). As vegetation establishes and pedogenic processes begin, alterations in soil surface characteristics can increase infiltration rates in reclaimed watersheds to near those of pre-mine levels (Jorgensen and Gardner, 1987). The dominant flow path from these reclaimed soils would likely change in response to increased infiltration.

This change in dominant flow path was observed for a reclaimed watershed in Pennsylvania (Guebert and Gardner, 1992). Infiltration rates increased steadily over four years to near pre-mine levels, but the surface discharge volume from the watersheds remained comparable. In tracer dye research the dominant flow path within these watersheds changed from infiltration-limited overland flow to subsurface flow through large macropores. The shape of the discharge hydrographs also changed indicating a change in flow paths. Year three hydrographs were characterized by a lower peak discharge, increased time to peak and longer flow duration than the year 1 hydrographs. Separation of the flow components of hydrographs simulated with the ANSWERS model indicated more of the discharge volume was attributed to saturation overland flow than infiltration-limited overland flow for year three compared to year one (Ritter, 1992).

Schroeder (1987) identified time since reclamation as a factor in reduced surface runoff from reclaimed areas in North Dakota. A rainfall simulator was used to generate surface runoff from three reclaimed areas of differing ages and two unmined grassland sites. Surface runoff and calculated curve numbers were lower for a 7-year-old reclaimed field than an adjacent 4-year-old site. Runoff from the 7-year-old site was comparable to the unmined grassland site when the soil profile was dry.

2.3. Topographic Features

Watershed shape and area, channel length and gradient, hillslope shape, gradient, and length are established during the recontouring of spoil material. Final landscape features of a reclaimed watershed determine the stability of the recontoured hillslope, the stability of the watershed channel and the shape of the storm hydrograph.

Increased slope gradient does not consistently translate into increased surface runoff and increased erosion. Surface runoff from a reclaimed hillslope with a 0.8% gradient was higher than that from a reclaimed hillslope with a 6.8% gradient (Schroeder, 1987). Investigation of the effects of slope gradient on soil loss/runoff relationships did not uncover any definitive trends when artifical rainfall was applied (Schroeder, 1989).

Warrington et al. (1989) investigated the effect of slope angle and addition of phosphogypsum on infiltration, runoff and soil loss. They reported no obvious relationships between slope angle and percentage of runoff for the untreated plots, but when phosphogypsum was added, percent runoff decreased with increasing slope angle. Soil loss for the untreated plots increased substantially when slope gradient was greater than 10%.

Slope gradient was an important factor in runoff and soil loss during snowmelt runoff from plots established on recontoured spoil (Gilley et al., 1977). Soil loss increased almost 200% for the 17.6% slope compared to a 4.8% slope. Percent of snow that became surface runoff was highest for topsoiled plots (71%), followed by the plots established on spoil material (48%) and was lowest for undisturbed rangeland (41%).

Dunne et al. (1991) identified that the failure to consistently measure differences in hillslope surface runoff when slope gradient or slope length is increased is partly explained by increases in overland flow depth. As the flow depth increases, more of the microtopographical high areas along the hillslope are inundated with surface runoff. These areas, which can be mounds of vegetation, have greater hydraulic conductivities and hence better infiltration rates than the depressional areas between the vegetation mounds. Apparent infiltration rate increases with the greater overland flow depth downslope.

2.4. Infiltration

Infiltration is the key hydrologic process that determines the quantity of incoming precipitation that becomes surface runoff and that which contributes to soil moisture or groundwater. Handling of the topsoil and subsoil material during mining, destroys much of the aggregation, porosity and pore continuity that had developed in an undisturbed soil (Indorante et al., 1981). Compaction of the subsoil and spoil material due to the conventional techniques of soil reconstruction also occurs (Felton, 1992). Reduced aggregation and porosity results in reduced infiltration capacity and infiltrated volume into reclaimed surface mined soils (Jorgensen and Gardner, 1987; Schroeder, 1989).

Average infiltrated volume into newly reclaimed surface mined soils in Pennsylvania was less than 25% of an undisturbed site with similar pre-mine soil (Jorgensen and Gardner, 1987). Measured infiltration rates were not correlated with any measured parameter the first year after reclamation, but after four years, infiltration parameters were significantly correlated with soil texture, vegetation, bulk density and slope gradient. Infiltration rates and 30-minute infiltrated volume increased yearly and recovered to near pre-mine levels four years after reclamation. Interestingly, the increase in infiltration rate and volume were not accompanied by an increase in any of the measured correlated parameters that explained most of the variance.

Infiltration rates were different in constructed topsoil/spoil profiles than in profiles constructed of only spoil material (Wells et al., 1982). Initial infiltration rates were high for the topsoil/spoil profiles due to well developed cracks that channeled flow down to the topsoil/spoil interface. Infiltration rates into the spoil material depended largely on the nature of the spoil material. Infiltration rates were low in well graded spoil with consistent particle size compared to coarse shale spoil material.

2.5. Erosion

Near surface replaced spoil material is material that was previously immediately overlying the coal seam. The material lacks structure and hence is easily erodible

(McIntosh and Barnhisel, 1993) and has not undergone weathering or pedogenic processes so it often retains or can develop adverse chemical characteristics (Rogowski et al., 1977).

Runoff and erosion is generally higher for bare spoil material than when subsoil and topsoil are replaced over the spoil material (Mitchell et al., 1983; McIntosh and Barnhisel, 1993). Rapid rilling and gullying of the exposed surface contribute the majority of the fine sediment in the surface runoff (Olyphant et al., 1991).

Controlling runoff and erosion from mined land is a major focus for mine operators. Reclamation success is largely determined by landscape stability and soil capability to support vegetation. The adverse impact of elevated levels of runoff and erosion from within the mine boundary can extend to receiving waters downstream and alter the stream environment (Touysinhthiphonexay and Gardner, 1984).

Channel stability is important for determining reclamation success. If ephemeral stream channels rapidly erode and are unstable the results are: increased erosion, unsightly landscape and additional expense. Assessing the condition of ephemeral channels in reclaimed watersheds in Colorado USA, Elliot (1990) found that the relationship between hillslope gradient, drainage area and the width of the channel bottom were fundamental in determining the stability of the watershed channel. His formula:

$$VEI_t = 28AGI^{0.19}W_v^{-1}$$

VEI = valley erosion index
AGI = area gradient index (area (acres)* gradient(ratio))
Wv = valley floor width (feet)

relating slope gradient and drainage area to channel width defined a threshold value that determined whether the channels of reclaimed watersheds were stable, or unstable and subject to erosion. Reclaimed channels with a valley-erosion index of less than 1.0 were considered stable and reclaimed channels with a valley-erosion index of greater than 1.0 were considered unstable.

Rapid establishment of a dense vegetative cover is considered the best erosion control measure. Olyphant and Harper (1995) were successful in reducing surface runoff and subsequent erosion from a spoil pile by direct revegetation. The amount of surface runoff per storm event for the revegetated watershed was less than one-third that of an unvegetated watershed.

Increasing the surface roughness of the spoil material is another strategy to reduce runoff and erosion from these spoil piles. Bulldozer tracks across the contour of the spoil were more effective in reducing surface runoff and erosion than imprints parallel to slope or back-bladed slopes (Bonta et al., 1991). Other techniques such as gouging, construction of basins, mulching and terracing (Meyer et al., 1970; Zuzel and Pikul, 1993), either alone or in combination have proved effective in reducing erosion from the spoil material.

Exposed unconsolidated spoil materials are easily eroded, but reconstructed mine soils are not necessarily more erodible than soils of unmined areas. At three mines located in Illinois and Indiana, Mitchell et al. (1983) found reconstructed mine soil less erodible than unmined soils under similar conditions. Schroeder (1989) reported similar results from rainfall simulator work on reclaimed and unmined grassland sites in North Dakota. Adjusted estimated soil losses for an undisturbed grassland site were higher than those from the reclaimed site.

2.6. Snow Hydrology

Snowmelt is the dominant surface runoff event for many areas with a continuous snow cover throughout the winter months (Hayhoe et al., 1993). Reduced infiltration into frozen soils at the time of melt translates into more water becoming surface runoff. On the prairies, approximately one third of annual precipitation occurs as snow but the snow cover can produce 80% or more of the annual surface runoff (Chanasyk and Woytowich, 1985; Granger and Gray, 1990; Hayhoe et al., 1993).

Many factors that control surface runoff for summer rainfall events are absent or play a lesser role determining surface runoff from snowmelt events. The influence of many soil features, flow mechanisms and topographic features of a watershed are reduced during snowmelt. Snowmelt runoff from hillslopes occurs primarily as infiltration-limited overland flow although subsurface flow through thin soils has also been observed (Wels et al., 1991).

Infiltration into a frozen soil can be restricted due to the nature and depth of the frost (Granger et al., 1984) and the condition of the soil/snow interface. Loose, granular frost in a dry, porous or cracked soil does not inhibit snowmelt infiltration. Conductivity of the frozen soil under these conditions remains high and much of the subsequent snowmelt can infiltrate (Marsh, 1990). Kane and Stein (1983) reported meltwater will freeze even in dry soils if the soil temperature is below freezing; infiltration proceeds unrestricted once the soil profile becomes isothermal at 0°C.

Available soil pore spaces are filled with water if the water content of the soil is high, either at the time of soil freezing or as a result of midwinter freeze-thaw cycles. When the water freezes, less pore space is available for transmission of the melt water in spring increasing surface runoff (Kane and Chaco, 1990). Fox (1992) conducted a sensitivity analysis of the parameters that determine soil freeze-thaw regimes and identified soil moisture as the most significant parameter that explained most of the variability of freeze-thaw depths. Soil moisture was also the dominant factor governing the amount of snowmelt infiltration (Granger et al., 1984; Kane and Chacho, 1990). Snowmelt infiltration was similar for soils of differing textures and land use but with similar soil moisture at the time of melt.

Ice layers can form at the snow/soil interface and within the soil profile as a result of a midwinter snowmelt period. Infiltration into the soil is impeded due to the frozen layer or layers and increased snowmelt surface runoff can be expected (Granger et al., 1984; Kane and Chacho, 1990). If a layer of frozen soil underlies a thin layer of thawed soil, saturation of the thawed layer results and flow from the hillslope can occur as subsurface or interflow through the thawed layer (Wels et al., 1991).

Evaporation from snowpacks is normally considered a minor component of the water balance equation (Bengtsson, 1980) and is commonly determined from lysimeter or snow pillow readings, or estimated from the water balance equation. Gieck Jr. and Kane (1986) estimated snowmelt evaporation within two watersheds in Alaska as 10 to 18% of total snow water equivalent. In another study of an Alaskan watershed, evaporation varied from 20 to 34% at the watershed scale but from four runoff plots located within the watershed, evaporation varied from 10 to 65% of total snow-water equivalent during 5 years of monitoring (Kane et al., 1991). In other studies summarized by Bengtsson (1980), evaporation rates were generally reported as less than one millimeter per day during snowmelt.

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3. RUNOFF QUANTITY AND QUALITY FROM TWO RECLAIMED WATERSHEDS

3.1. Introduction

Most geographic, pedologic and vegetative parameters contributing to the surface hydrology of undisturbed watersheds are altered during the reconstruction and reclamation phases of surface mining. These parameters include: watershed size and shape, channel length and gradient, hillslope length and gradient, soil morphological and physical parameters and vegetation type and density. As a consequence, the quantity and quality of surface runoff from reclaimed surface-mined watersheds is expected to be altered. In the United States, the Surface Mining Control and Reclamation Act of 1977 legislates that post-reclamation surface hydrology must be similar to pre-disturbance surface hydrology. No equivalent legislation exists in Canada.

Surface runoff from reclaimed surface-mined watersheds occurs when rainfall intensity exceeds the soil's infiltration capacity and during snowmelt when the frozen soil limits meltwater infiltration. Infiltration into newly reclaimed surface-mined soils is characteristically low (Wells et al., 1982; Jorgensen and Gardner, 1987) as a result of increased bulk density (Indorante et al., 1981; Wells et al., 1982) and reduction of porosity during removal and replacement of topsoil and subsoil (Wells et al., 1982). Infiltration-excess overland flow is likely the primary flow process occurring within newly reclaimed surface-mined watersheds (Ritter and Gardner, 1993). As the infiltration rate recovers to near pre-mine levels, dominant flow processes can change to saturation overland flow (Ritter and Gardner, 1993) or subsurface flow via macropores along the hillslopes (Guebert and Gardner, 1992).

Although snow accounts for less than 25% of total annual precipitation in central Alberta (Environment Canada, 1982), snowmelt runoff can account for upwards of 80% of annual surface runoff within this area (Chanasyk and Woytowich, 1985; Hayhoe et al., 1993). Gilley et al. (1976) found snowmelt hydrographs were characterized by a gradual rising limb, sustained peak and a gradual recession limb whereas rapid responses and higher peak discharge typified hydrographs from rainfall events.

Erosion from mine-spoil on reclaimed watersheds and subsequent high suspended solids in the runoff water is often a major concern of mine operators. The highest erosion risk on mining sites are usually on the spoil materials (McIntosh and Barnhisel, 1993; Olyphant and Harper, 1995), but erosion can be controlled by establishment of a dense vegetative cover (Olyphant and Harper, 1995), by surface microtopographic manipulation of the spoil slope (Bonta et al., 1991) or by using mulches such as straw (Zuzel and Pikul Jr, 1993). Erosion from well-vegetated reclaimed surfaces is often less than that for similar undisturbed areas under similar pre-rainfall conditions (Mitchell et al., 1983; Schroeder, 1989).

There are very few studies quantifying the contribution of snowmelt runoff to annual surface runoff and erosion from reclaimed surface-mined watersheds. Snowmelt runoff is perhaps the most important hydrologic event of the year in central Alberta. Equally, detailed watershed runoff studies on reclaimed watersheds either at the hillslope or entire watershed scale do not exist for central Alberta.

The principal objectives of this study were to quantify surface runoff for both summer storm events and spring snowmelt, assess the quality of this surface runoff, and identify the dominant runoff processes operating from two reclaimed watersheds. The hypotheses tested for the two reclaimed watersheds were: (i) summer rainfall and snow melt contribute equally to total surface runoff or instantaneous peak flows in the two reclaimed watersheds; (ii) water quality from the two reclaimed watersheds is within guidelines specified; and (iii) the dominant hydrologic flow paths are the same or similar between the two reclaimed watersheds.

3.2. Study Area and Description of Watersheds

The study area consists of two reclaimed watersheds located within the TransAlta Utilities Highvale Mine boundary, approximately 80 km west of Edmonton, Alberta (114°34' N Lat., 53°29' W Long.) on the south shore of Lake Wabamun (Figure 3.1). The watersheds are approximately 2 km apart.

The Sandy Subsoil Watershed (Figure 3.2) was constructed in 1989 to 1990, and revegetated with a forage mix of: alfalfa (*Medicago sativa)*, smooth brome (*Bromus inermis*), reed canary grass (*Phalaris arundinacea*), Canada bluegrass (*Poa compressa*), creeping red fescue (*Festuca rubra*) and timothy (*Phleum pratense*); using an oat companion crop for the first year. Typical soil profiles are a 20- to 40-cm topsoil layer of loam to clay loam texture and a fairly homogeneous subsoil layer of sandy loam texture to depth.

The West Watershed (Figure 3.3) was reclaimed in 1991 to 1992 and revegetated with a similar forage mix as the Sandy Subsoil Watershed. A rye crop was companion seeded. The reconstructed soil profile is comprised of a loam to clay loam topsoil layer of approximately 20 cm depth overlying a 1.5-m subsoil layer of clay loam texture, overlying clay textured mine spoil (see Table 3.1 for a complete description of the two watersheds).

3.3. Methods and Materials

3.3.1. Meteorology

The meteorological station on the Sandy Subsoil Watershed was established in early summer 1992. A Campbell Scientific CR21X datalogger was used to continuously monitor air temperature, relative humidity, wind speed, wind direction, solar radiation, rainfall intensity, soil temperatures and snow depth. A second meteorological station was established at the West watershed in fall 1993. A Campbell Scientific CR10 datalogger was used to continuously monitor the same meteorological parameters as the Sandy Subsoil watershed except solar radiation. Six standard rain gauges were placed within and outside of the mine boundary in 1993 to quantify the areal distribution of precipitation during summer rainfall events. The representativeness of precipitation and temperature during the study period to long term normals was done by comparison to the 28 year record from Stony Plain, located 35 km east of the study site.

3.3.2. Soil Moisture

Soil moisture and soil temperature measurements began in 1992 adjacent to each of the microframes and along the channel within both watersheds. Soil moisture profiles were measured at 10-cm depth intervals to a depth of approximately 95 cm starting at 15 cm with a CPN 503 moisture probe. Near-surface soil moisture was determined using a neutron probe with a surface shield (Chanasyk and Naeth, 1988). Soil moisture was routinely sampled at two-week intervals throughout spring, summer and fall 1993, 1994 and 1995. When possible, soil moisture was also sampled prior to and shortly after a rainfall event.

3.3.3. Bulk Density

Soil bulk density profiles were measured at 10-cm intervals to a depth of around 95 cm starting at 15 cm with a CPN 501 combination soil moisture/density probe in the spring and fall of each year. A CPN MC1 combination surface soil moisture/bulk density gauge was used to measure near-surface (0-7.5 cm) soil bulk density.

3.3.4. Soil Temperature

Nests of thermistors to measure soil temperature were installed in the soil adjacent to each of the microframes on the Sandy Subsoil Watershed and at each slope gradient and aspect on the West Watershed at depths of 5, 10, 20 and 40 cm. Temperature was measured with a hand-held multimeter prior to spring snowmelt and once or twice in the afternoon during snowmelt 1993 and 1994. Continuous soil temperature measurements were obtained from a nest of thermistors (depths of 5, 10 and 20 cm) installed adjacent to the meteorological station and connected to the datalogger.

3.3.5. Vegetation

Both watersheds were vegetated with a grass/legume mix that was hayed twice yearly. Fertilizer was broadcast in spring 1993, 1994 and 1995 in approximate amounts: 88 kg ha^{-1} nitrogen, 32 kg ha^{-1} phosphorous (P_2O_5), and 14 kg ha^{-1} sulphur. Vegetation canopy height, species composition, litter depth and ground cover were assessed for each microframe at least once per growing season.

3.3.6. Snow Depth and Water Equivalents

Accumulation/ablation of the snowpack was continously monitored in both watersheds at each meteorological station with an ultrasonic depth sensor connected to a datalogger. Snow depth measurements were also taken manually adjacent to each microframe and along the hillslopes and channels with a snow core sampler prior to spring snowmelt each year. Spring snowmelt was defined as the period of sustained melt when most of the surface runoff occurs.

Between 30 and 40 measurements per watershed were obtained to determine average snow depth, and ten samples per watershed were retained and brought to the lab for weighing to determine average snow density. These measurements were taken on February 25 and March 13 in 1993, March 2 in 1994 and February 1 and March 8 in 1995. In 1993, an average value for the entire watershed was used for determining snow-water equivalents prior to snow melt. An average value for three frames on similar slope and aspect was used for snow water equivalents (SWE) for the March 13 sampling date within the West Watershed. In 1994, SWE were determined for each frame separately.

Monthly snowfall amounts for the watersheds were obtained from the Stony Plain meteorological station.

3.3.7. Retention Storage

Channel retention storage within each watershed was estimated at the end of the snowmelt period when flow was still trickling through the watersheds and the depressions were full. The surface area of the depressions was divided into a 1 x 1 m grid and depth measurements were taken at each node. The computer program SURFER was used to calculate the volume of each mapped depression.

3.3.8. Hillslope Overland Flow

Hillslope overland flow was measured using 1-m^2 runoff frames pounded approximately 6 cm into the ground. Overland flow originating from within the frame border was routed through a hose into a series of three below-ground collection buckets that increased in volume from 4 L to 64 L (Figure 3.4). The frames were constructed such that 1.0 mm of runoff equalled 1.0 L of runoff within the collection buckets. Within the Sandy Subsoil Watershed, the frames were located on two slope aspects (north and south), at two slope positions (upper and lower) and replicated three times for a total of 12 frames. Microframes within the West Watershed were located on two slope aspects (north and south), at two slope gradients (13% and 5%), replicated three times for a total of 12 frames. The volume of runoff within the collection buckets was measured after each rainfall event during the summer and at least daily during snowmelt.

Problems with the collection buckets were encountered during a January 1993 midwinter melt and modifications were made to the installation of the collection buckets. A plywood cover over the top of the largest bucket was deemed necessary to prevent snow and ice from collecting and submerging the bucket. A further problem with the installation was identified during the snowmelt period of 1994 when daily surface runoff upslope of the microframes would buildup and freeze behind the microframe border during the evening. Further upslope surface runoff would then flow over the frame border and contribute to volume collected from the frame.

A tipping bucket rain gauge connected to the datalogger was placed within the 64-L pail at microframe SNL3 within the Sandy Subsoil watershed (see Figure 3.2). The timing and volume of hillslope runoff at this frame was recorded at the same frequency as rainfall intensity. This enabled a comparison of the timing of hillslope runoff to watershed surface runoff and also indicated the commencement of water release from the snowpack.

3.3.9. Watershed Runoff

A two ft. H-flume located at the outlet of each watershed was used to monitor stage of runoff (Figure 3.5). The H-flumes were installed in late fall 1992, and were manually monitored and calibrated during snowmelt 1993. The manual calibration and monitoring of discharge was conducted by collecting a volume of runoff from the outlet of the H-flume in a 20-L pail and timing the duration that the pail was in the flow. The volume collected divided by the duration gave discharge (litres) per unit time (seconds). Flow was monitored at 30-minute intervals commencing at around 0930 h (local time) each morning of snowmelt until dark (usually around 1800 h). Peak daily discharge during melt usually occurred in late afternoon. Manual monitoring the 1993 snowmelt meant much of the recession limb of the hydrograph was not measured since it was dark when discharge was decreasing from the watersheds. Recession limbs were estimated for this period by assuming flow stopped when ambient air temperature dropped below 0 °C (see Figure 3.6 for example). If hourly temperatures did not drop below 0 °C, the overnight sustained flow was estimated from the first reading of flow the following morning.

Stevens water level recorders equipped with a mechanical clock and charting mechanisms were installed in the stilling well at each Watershed in early summer 1993. The mechanical clock and charting mechanisms on each recorder were replaced with a ten-turn potentiometer in August 1993. This modification enabled digitized recording of the stage readings with a datalogger programmed to sample stage every 15 minutes. During snowmelt 1994 and 1995, ice formed in the stilling well at night, freezing the float in position before flow ceased. Hydrographs were adjusted assuming that flow ceased when nightly temperatures dropped below 0 °C.

3.3.10. Water Quality

Four 250-mL samples or one 1000-mL sample were collected from the watershed outlet periodically throughout the day during snowmelt runoff events for determination of total suspended solids (TSS), pH, electrical conductivity (EC), nitrate nitrogen, ammonium nitrogen and total phosphates. Four 250-mL samples were obtained from the runoff volume at each microframe for the same analyses except N and P.

TSS (mg/L) for the runoff samples were determined by filtration and air drying to constant weight (24 h). EC and pH were measured with a conductivity bridge and pH meter, respectively. Nitrate nitrogen, ammonium nitrogen and total phosphorous for the runoff samples were determined with an auto-analyzer.

3.4. RESULTS

3.4.1. Meteorology

Long-term annual precipitation reported at the Stony Plain meteorological station is 528.8 mm with 21% occurring as snow and average annual temperature is 3.3°C (Environment Canada, 1982).

Summer rainfall at the study sites was near or slightly above Stony Plain long-term-normals (LTN) for May, June and July 1993 but August, September and October precipitation was less than 50% of the LTN. Rainfall in 1994 was below the LTN for all months except June. Precipitation in 1995 was below normal in May and June, slightly higher in July and well above normal in August (Table 3.2).

Average summer temperatures from May to August for all years were within 1 °C of the LTN (Table 3.3). Summer months with the greatest deviation from the LTN both hotter and cooler, were May 1993 and August 1995, respectively (Table 3.2).

Snow accumulation during winter 1992-1993 was 72% of the LTN for November 1992 through to March 1993. January and February snowfall amounts were extremely low and well below LTN resulting in a fairly shallow snowpack at the commencement of snow melt on February 27, 1993. Snow accumulation for November 1993 through March 1994 was slightly above the LTN. Near record snowfall occurred in January 1994 comprising nearly one-half of the total winter accumulation. Snow accumulation during the winter of 1994-1995 was only 40% of the LTN (Table 3.2).

Winter temperatures for most months were near normal for all three years. A near record low monthly temperature for February 1994, was an exception (Table 3.2).

3.4.2. Bulk Density

Average profile bulk density was numerically higher for the Sandy Subsoil Watershed than for the West Watershed (Figure 3.7). Average bulk density for the 45-85 cm depth interval ranged from 1.3 to 1.9 Mg m^{-3} for the Sandy Subsoil Watershed and from 1.1 to 1.8 Mg m^{-3} for the West Watershed. There was considerable variation of bulk density with depth among sampling locations, with the greatest variation along the hillslopes, particularly for the 15-45 cm depths (Figure 3.8).

3.4.3. Snow Depth and Water Equivalent

Snow-water equivalents for the microframes and the watersheds are shown in Table 3.4. Snow accumulation and snow water equivalents prior to snow melt were nearly twice as much for snowmelt 1994 than in 1993 and 1995. Unlike the 1993 snowmelt, the melt in March 1994 was interrupted only once by a prolonged period of below freezing daytime high temperatures. There were no subsequent snowfall additions once melt started.

A melt commencing around January 29, 1995 resulted in almost total snow ablation from the south-facing slope of the Sandy Subsoil Watershed. Snow-water equivalents were determined on February 1 from the depth, density and extent of the remaining snow coverage. Snow depth and density measurements were also taken on March 8, but a discontinuous ice layer under the thin snow covering made quantification of snow densities extremely difficult. The depth of the ice layer was measured at various points and a density value for the ice of 0.92 g cm^{-3} was assigned (Dingman, 1994). There was no snowmelt runoff from the West Watershed during the late January 1995 melt, therefore, snow-water equivalents could be determined fairly accurately.

3.4.4. Soil Moisture

End of August soil moisture profiles from both watersheds were similar for 1993 and 1995 (Figure 3.9), but lower for 1994; a reflection of the low summer precipitation in 1994.

Soil moisture was consistently higher in the West Watershed than in the Sandy Subsoil Watershed (Figure 3.10). Standing water remained within channel depressions in the West Watershed for extended periods after a precipitation event. Infiltrated precipitation would occasionally fill the soil moisture access tubes on the south-facing 5% slope and the furthest west channel tubes to a depth of approximately 45 cm, indicating perching of water near the surface. Water holding capacity of the clay to clay loam subsurface material within the West Watershed was higher (37% @ 33kPa) than in the sandy loam subsurface material (17% @ 33kPa) of the Sandy Subsoil Watershed.

Average soil moisture remained consistently higher on the north-facing than the south-facing slopes within the Sandy Subsoil Watershed (Figure 3.11). Aspect did not have the same influence on soil moisture in the West Watershed (Figure 3.12).

3.4.5. Retention Storage

Channel storage was greater for the Sandy Subsoil Watershed (1.4 mm) than for the West Watershed (0.8 mm). The major channel depression in the West Watershed was located about 32 m from the outlet, whereas in the Sandy Subsoil Watershed it was located approximately 74 m from the outlet.

3.4.6. Hillslope Overland Flow

The microframes worked reasonably well to quantify total runoff from natural rainfall events. Average summer rainfall runoff volumes for the frames located in the Sandy Subsoil Watershed for 1993, 1994 and 1995 were 88, 30 and 64 mm, respectively (Figure 3.13). However, one frame (SSL2) yielded the majority of the runoff. Hillslope length and gradient are not as pronounced within the West Watershed as in the Sandy Subsoil Watershed, and hillslope frame runoff volumes in 1993, 1994 and 1995 were 26, 0.4, and 25 mm, respectively (Figure 3.14). Snowmelt runoff volumes for hillslope microframes in the Sandy Subsoil Watershed for 1993, 1994 and 1995 were 38, 82 and 54 mm, respectively and for the West Watershed for the same years were 53, 68 and 44 mm, respectively.

Snowmelt runoff volumes for hillslope microframes varied widely in amount and timing both between and within watersheds. Aspect influenced the amount and timing of snowmelt runoff within both watersheds. (Table 3.5).

3.4.7. Hillslope Frame Runoff Quality

Soil disturbance at the time of installation is likely responsible for the higher concentrations of suspended sediment in the runoff from the hillslope frames in 1993 than in 1994 or 1995. EC was generally low for both summer rainfall and spring snowmelt runoff and pH was consistently near neutral (Table 3.6).

3.4.8. Watershed Runoff

3.4.8.1. Summer

Hillslope runoff occurred during 11 rainfall events in 1993, 16 in 1994 and 15 in 1995 but flow from the Sandy Subsoil Watershed occurred only twice during the study period. The 1993 rainfall event that initiated flow occurred on July 21 when 78 mm of rainfall was recorded during an 18 hour period. Peak 5-min rainfall intensity for this event was 72 mm h^{-1} occurring 7 hours after the commencement of rainfall. Discharge at the outlet peaked at 4.2 L s^{-1} and watershed equivalent volume of 1.8 mm was calculated from the strip charts (Figure 3.15). The runoff-producing 1995 rainfall event occurred on August 16 when 42 mm of rain fell in 2 h 10 min. Peak 5-min rainfall intensity was 132 mm h^{-1}, peak discharge from the watershed was 19.6 L s^{-1} and volume was 8.1 mm (Figure 3.16).

Flow from the West Watershed occurred three times during summer 1993, not at all during summer 1994, and five times during summer 1995. Peak flow of 14 L s^{-1} occurred during the July 21,1993 rainfall event, but the timing and duration of flow was not recorded due to instrument failure. The timing and duration of flow from the West Watershed for this event was estimated from the hydrograph trace from the Sandy Subsoil Watershed; volume of runoff was estimated at 2.4 mm. Flow was recorded from the West Watershed in summer 1993 during two rainfall events of lesser intensities and amounts than the July 21 storm. On June 22, a two-day rainfall of 54 mm in 34 hours resulted in peak flow of 3 L s^{-1} and total volume of 0.7 mm. On June 27, a rainfall event of 26 mm of duration 2 hours 55 minutes with a peak 5-min intensity of 72 mm h^{-1} resulted in surface runoff volume of 0.1 mm with a peak flow of 2.4 L s^{-1} (Figure 3.17). Five rainfall events in 1995 resulted in flow from the West Watershed. A rainstorm on July 25 when 35 mm of rain fell in 2 h resulted in a peak flow of 9.3 L s^{-1} and a total volume of 1.3 mm (Figure 3.18). Peak flow of 79 L s^{-1} occurred on August 16 when 42 mm of rain fell in a 2 h 10 min time period. Total runoff volume was 11 mm watershed equivalent depth (Figure

3.19). There were three other flow events in August 1995 with peak flows of less than 2.0 L s^{-1} (Figure 3.20).

3.4.8.2. Winter

Snowmelt of February 27 to March 8, 1993 was the first measured surface runoff event from the watersheds. The discharge channel on the Sandy Subsoil Watershed was inadequate during this melt and flow backed up into the H-flume making stage readings unreliable. The channel was re-graded prior to the two later March 1993 snowmelt events. Snowmelt surface runoff from the West watershed for the snowmelt period was monitored successfully.

Total runoff volume from the West Watershed for the snowmelt period February 27 to March 6, 1993 was 19.5 mm equivalent depth. Peak flows of near 27 L s^{-1} occurred on February 28 and March 2 (Figure 3.21). The runoff coefficient (runoff (mm)/water equivalent (mm)) was 0.33. By March 7 the flume was trickling and the last of the snow melted from the north-facing steep slope. Daily maximum temperatures dropped below freezing by March 10 and by March 13 (when the snow survey was done) a snowfall of 6 to 8 cm had accumulated on the West Watershed. A second melt commenced March 20. Snowmelt volume from the West Watershed was 4 mm and the runoff coefficient for this second melt was 0.22.

Snow accumulation prior to the March 20 melt was less uniform on the Sandy Subsoil Watershed than on the West. The south-facing aspect was clear of snow, 2-4 cm snow depth occurred in the channel and a uniform 6-7 cm accumulated on the north-facing aspect. Although the channel on the Sandy Subsoil Watershed was re-graded prior to the March 20 melt, there was no flow. A late March snowfall that deposited up to 3 cm on the watersheds did not result in any flow from either watershed.

There were two major snowmelt events during winter 1993-1994. In mid-December 1993, there was an accumulation of up to 10 cm of snow that melted December 24 and 25 (Figure 3.22). Both the Sandy Subsoil and West Watersheds were clear of snow after this melt but there was no surface runoff from the watersheds. The principal melt period occurred March 12-31.

The 1994 melt from the Sandy Subsoil Watershed occurred from March 11 to 16. There was a trickle from the flume until March 18, but the stage was less than 1 cm. Total snowmelt runoff volume was 40 mm. Maximum daily peak discharge of 33 L s^{-1} occurred March 13 (Figure 3.23).

Flow from the West Watershed commenced March 13, two days after melt started from the Sandy Subsoil. Flow was interrupted from March 19 to 24 as daily maximum temperatures remained below freezing. Total snowmelt runoff volume was 33 mm. Maximum peak discharge of over 32 L s^{-1} occurred on March 25 (Figure 3.24).

There were four periods of above 0 °C maximum daily temperatures during winter 1994-1995 (Figure 3.25). There was no flow from either watershed for the mid-December and January 29 to February 1, 1995 melt periods. Flow of less than 0.1 L s^{-1} occurred from the Sandy Subsoil Watershed from February 21-24, 1995. Snowmelt runoff began from both watersheds from March 11 to 17. In both watersheds, areas on the south-facing slope were clear of snow prior to the melt, thus there were areas within the watersheds that were not contributing to snowmelt runoff. Total snowmelt runoff from the Sandy Subsoil Watershed was 7.4mm during this period and peak discharge of 4.1 L s^{-1} occurred on March 12 (Figure 3.26). Total snowmelt runoff from the West Watershed was 6.4 mm with a peak discharge of 16 L s^{-1} occurring on March 12 (Figure 3.27).

3.4.9. Watershed Runoff Water Quality

Average phosphorous (PO_4) and nitrogen (NO_3) concentrations in the runoff were slightly above background levels for Lake Wabamun (Habgood, 1983), but never exceeded the limit specified (1.0 ppm) in the Sundance power Licence to Operate (no. 91-WL-031) for discharge into Lake Wabamun (Monenco, 1992). Phosphorous levels in runoff from the West Watershed increased from 1993 to 1995 to levels higher than specified in Alberta Surface Water Quality Objectives (< 0.15 ppm) and are at or above levels of total phosphorous within streams draining into Lake Wabamun (AEP, 1985)(Table 3.10). Electrical conductivity remained low and pH was consistently near neutral.

Total suspended solids were high in 1993 (Table 3.7) likely due to installation of the flumes and frames which disturbed the soil. Total suspended solids were lower in 1994 after the vegetation re-established on the disturbed areas in both watersheds (Table 3.8) and further reduced to negligible levels in 1995 (Table 3.9).

3.5. DISCUSSION

3.5.1. Watershed Runoff

The dominance of snowmelt runoff for prairie environments evidenced in previous studies on unmined areas (Chanasyk and Woytowich, 1985; Hayhoe et al., 1993), is generally characteristic for reclaimed areas (86-100% in this study) in central Alberta during years of "normal" snow accumulation. Only with record low snowfall or near record high rainfall during some summer months did snowmelt runoff account for less of total annual runoff (31- 48% in this study).

Snowmelt maximum peak flows from the West Watershed were consistent and comparable for study years 1993 and 1994 (27 L/s and 33 L/s respectively) even though the snow water equivalent for the 1994 melt period was more than double that for the 1993 melt period. Maximum peak flow for the 1995 snowmelt period were only 16 L/s, but considering snow-water equivalents prior to melt in the West Watershed in 1995 were less than 25% of what they were in 1994, maximum peak flow in 1995 was just under 50% of what it was in 1994. Increased soil moisture during the mid-winter melts of 1994-1995, and formation of a surface ice layer probably contributed to higher discharge from the watersheds in 1995 than would have occurred if the snowpack had been stable throughout the winter.

Snowmelt is governed by energy exchanges at the snow/air and snow/soil interface (Dingman, 1994). It would seem reasonable that the rate of liquid water release from the snowpack, and hence peak flow, would be dependent on these energy exchanges, whereas total volume of snowmelt runoff would be dependent on the depth and density of the snowpack and extent of contributing area.

The highest recorded peak discharge from the Sandy Subsoil Watershed during the three years of monitoring occurred during snowmelt in March 1994. Surprisingly, peak flow from the watershed during the August 16, 1995 rainfall event did not exceed the highest snowmelt peak flow; antecedent soil water conditions in August 1995 were at the highest level in three years and there was standing water in the channel depression in summer for the first time in three years. The channel within this watershed seems to be the area that determines the amount of discharge. In contrast to other studies that have identified the channel area as being a source for overland flow due to saturation via a rise in the water table (Dunne and Black, 1970); convergence of flow (Anderson and Kneale, 1982; Burt and Butcher, 1985); or translatory flow of pre-event water (Waddington et al., 1993), the channel within this watershed behaves as a sink for overland flow generated from the hillslopes.

Dunne et al. (1991) stated that increased depth of flow enhanced infiltration due to a greater portion of the landscape being inundated by surface flow. Enhanced infiltration occurring along the channel within this watershed would in part explain the low runoff during major summer storms.

A well vegetated channel provides resistance to overland flow and allows more time for surface runoff to infiltrate (Dunne et al., 1991). The channel within the Sandy Subsoil Watershed is very well vegetated with minimal exposed bareground and could slow overland flow to allow more of the surface flow time to infiltrate.

Soil texture is an important factor in determining infiltration rate and infiltrated volume from reclaimed surface-mined watersheds (Jorgensen and Gardner, 1987). The sandy loam texture of the subsoil material in this watershed would be expected to have high hydraulic conductivity and therefore a high constant percolation rate (Meek et al., 1992). In preliminary infiltration studies on similar subsoil material in 1992, rates into the subsoil material were very low (Dell, unpublished); in sharp contrast to conventional thinking. Although not verified, it was speculated that the upper surface of the subsoil material has fragipan characteristics that when dry, limits percolation. Percolation is not impeded when the subsoil material is moist due to the loose, friable and cohesionless nature of the subsoil material when moist. Soil moisture was highest along the channel area and therefore percolation could proceed unrestricted.

In contrast to the Sandy Subsoil Watershed where highest peak flow occurred during snowmelt 1994, the highest peak flow from the West Watershed occurred during the August 16, 1995 rainfall event. High antecedent soil water conditions and standing water within the depressions of the watershed prior to this major rainfall event contributed to the high peak discharge. High peak flows at this watershed relative to the Sandy Subsoil Watershed also occurred during the July, 1993 runoff event. Less intense rainfall events of moderate to long duration also initiated flow from this watershed. The channel and near channel areas appear to be critical in determining this watershed's response to summer rainfall events. Unlike the Sandy Subsoil Watershed where enhanced infiltration occurred in the channel area, the channel within the West Watershed is a source area for overland flow.

The magnitude of dominant flow paths was different between the two watersheds. Surface runoff from the Sandy Subsoil Watershed occurred only during the most intense summer storms monitored when the highest peak 5-min intensities were recorded. In the West Watershed, flow occurred during less intense summer storms when a period of rainfall preceded the runoff event and during long duration, low intensity rainfall events. Recent analysis by Larsen et al. (1994) on runoff behaviour from seven catchments in Australia identified two dimensionless parameters related to soil hydraulic properties and topography that can be used to determine catchment behavior to rainfall events. The researchers concluded that in five of the catchments, saturation overland flow dominated the runoff response, and in the remaining two catchments, infiltration-excess overland flow was the dominant flow process. Similar dominant flow processes were obtained on reclaimed watersheds in Pennsylvania by Ritter (1992) when he parameterized the ANSWERS model for predicting watershed runoff. Runoff could be reasonably predicted from the watershed where infiltration-excess overland flow was the dominant flow path, but where saturation overland flow occurred, prediction success was only marginal.

Infiltration-excess overland flow was the dominant flow path occurring within the Sandy Subsoil Watershed whereas saturation overland flow dominated within the West Watershed. Overland flow from the hillslopes of the West Watershed did not occur consistently during the lesser rainfall events that initiated watershed runoff. This indicates the source of the watershed runoff for these lesser events was not from the hillslopes, but rather from source areas along the channel and near-channel areas. This is not unusual as saturated areas within watersheds that contribute the majority of runoff have been identified in a number of other studies (Beven et al., 1988; Allan and Roulet, 1994).

3.5.2. Hillslope Microframes

Snowmelt overland flow from the hillslope frames in the West Watershed accounted for 67% of the annual runoff in 1993, almost 100% in 1994 and 64% in 1995. Hillslope surface runoff from summer rainfall in this watershed occurs infrequently and only during long duration rainfall events. As an example, hillslope surface runoff occurred during only 4 of the 15 rainfall events in 1995, and a few of the hillslope microframes did not produce any runoff during these events.

Snowmelt runoff accounted for less of the annual frame surface runoff from the hillslopes of the Sandy Subsoil Watershed than the West Watershed; 30%, 73%, and 46% of the total hillslope runoff in 1993, 1994 and 1995, respectively. Hillslope surface runoff from at least a few of the frames occurred during most of the rainfall events in the three years of study, and often surface runoff from all 12 of the frames would occur. In contrast to the West Watershed, some hillslope surface runoff occurred during all 15 rainfall events of 1995 in the Sandy Subsoil Watershed.

Surface runoff from the hillslope microframes for summer precipitation events was dominated by the frames located within the Sandy Subsoil Watershed. Average hillslope runoff for rainfall events from the Sandy Subsoil Watershed compared to the West Watershed averaged 88 mm vs. 26 mm for 1993, 30 mm vs 0.04 mm for 1994 and 64 mm vs. 25 mm for 1995.

Bulk density was one of the factors explaining variability of infiltration into reclaimed watersheds in Pennsylvania (Jorgensen and Gardner, 1987). Meek et al. (1992) found that an increase in bulk density from 1.6 Mg m^{-3} to 1.8 Mg m^{-3} decreased average infiltration rates by 54% in a sandy loam soil. Average surface bulk density (0-12.5 cm) was slightly higher for the frames located on the Sandy Subsoil Watershed (Figure 3.8), but the greatest difference in bulk density between watersheds was at the 35 cm to 45 cm depth. The topsoil/subsoil interface within the Sandy Subsoil is normally at this depth and bulk densities were greater than 1.7 Mg m^{-3} for some locations along the hillslopes at these depths.

One frame within the Sandy Subsoil Watershed (SSL2) accounted for nearly one quarter of hillslope frame runoff in 1993 and 1995, and close to 93% of hillslope runoff in 1994. The runoff coefficient for this frame was occasionally greater than 1.0 for isolated rainfall events. Attempts to explain why the flow process was so different for this one frame included installation of soil moisture blocks above the frame at varying depths, channeling into the subsurface away from the collection bucket and using a penetrometer to reveal subsurface topography. Visual observations within and around the frame hinted that the flow process was different at this particular frame. The vegetation was sparser and not as green as the vegetation on the rest of the hillslope. During rainfall events, the litter layer within the frame appeared to be lifting and surface water would accumulate at the discharge end of the frame. An ice layer remained above the frame during the melt period for many days after surface runoff from the hillslope had finished. Although not quantified, subsurface contributions to surface flow (return flow) appeared to be occurring at this hillslope location. Guebert and Gardner (1992) hypothesized the same flow process occurring at a watershed scale within an older reclaimed watershed in Pennsylvania.

3.5.3. Runoff Quality

Total suspended solids from snowmelt runoff declined each year to levels within those considered acceptable for discharge (AEP, 1978). Although no samples of runoff for suspended sediment determination were obtained from the watersheds during major summer rainfall events, total sediment has been shown to decrease substantially in watersheds when dense vegetation is established after reclamation (Olyphant and Harper, 1995). Suspended sediment from the two study watersheds should remain low providing the present vegetative cover is maintained.

Higher total phosphorous in runoff from the West Watershed compared to the Sandy Subsoil Watershed is unexpected since the topsoil material is similar, both watersheds were revegetated with the same species composition and the amount, timing and type of fertilizer applications were the same. Higher phosphorous concentrations from the West Watershed may be a consequence of the different dominant overland flow pathways within the two watersheds. Higher phosphorous levels would be expected when watershed runoff is comprised of not only event but also pre-event water from within the soil profile.

3.6. CONCLUSIONS

The majority of annual runoff from reclaimed watersheds during years of "normal" or below normal precipitation will be from snowmelt. Flow from summer rainfall for the two reclaimed watersheds is not as consistent as it is during snowmelt since rainfall events in the order of a 1:10 year return period or greater are necessary to initiate substantial flow from the two reclaimed watersheds.

As long as the energy inputs to the snowpack remain comparable between years, and all areas of the watershed contribute, maximum peak flow should remain consistent across years. Peak discharge from snowmelt was comparable and consistent between 1993 and 1994 for the West Watershed, even though snow accumulation prior to melt was substantially different from year to year. High peak discharge may occur during intense summer rainfall events, but the magnitude of the peak varies, depending on the nature of the dominant flow processes operating within the watershed.

The Sandy Subsoil Watershed responds with flow only during the most intense summer rainfall events, even though the hillslopes are very effective in producing runoff during many smaller rainfall occurrences. Infiltration-excess overland flow is likely the dominant flow process occurring within the Sandy Subsoil Watershed but channel losses within this watershed dampen the magnitude of peak flow. The West Watershed maintains high antecedent soil moisture during the rainfall period, depressions often remained filled after precipitation events, there are areas of near surface saturation within the watershed, the watershed responds with flow for lesser rainfall events even when no hillslope surface runoff occurs and the hillslopes do not consistently produce runoff during rainfall events. These factors combined suggest saturation overland flow as the dominant process occurring within this watershed during summer rainfall events.

Aspect is an important factor in determining soil moisture of the hillslopes and therefore surface runoff. The north-facing aspect of the Sandy Subsoil Watershed had consistently higher soil moisture than the south-facing aspect and surface runoff from the north-facing aspect dominated surface runoff from this watershed. Aspect was not as major a factor in the West Watershed; soil moisture was usually higher along the south-facing aspect, and the south-facing aspect generated the most surface runoff. However, aspect is important in determining the timing and amount of hillslope surface flow during the snowmelt period. South-facing hillslopes clear of snow the earliest, and contribute the least to watershed runoff.

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Table 3.1. Physical description of reclaimed watersheds

	Sandy Subsoil Watershed	West Watershed
Size	3.4 ha	9.84 ha
Aspect	North and South-facing slopes	North and South-facing slopes
Shape	Convergent	Convergent
Vegetation	Permanent forage	Permanent forage
Channel Storage	46.5 m^3 or 1.4 mm[a]	74.5 m^3 or 0.8 mm[a]
Slope Length (m)		
North-facing	100	100
South-facing	42	110
Slope Steepness	North-facing 16% South-facing 17%	Steep 13 % Flat 6%
Channel Length	230 m	570 m
Channel Gradient	0.37%	0.97%

[a] - watershed equivalent depth

Table 3.2. Temperature and precipitation data for November 1992 to September 1995

Month	Stony Plain		Highvale		Stony Plain (LTN)*	
	Ppt (mm)	Temp (°C)	Ppt (mm)	Temp (°C)	Ppt (mm)	Temp (°C)
Nov-92	25.1	-1.5	-	0.3	21.4	-4.2
Dec-92	21.0	-13.6	-	-11.8	26.1	-10.1
Jan-93	2.8	-12.2	-	-15.1	24.5	-12.1
Feb-93	9.8	-8.1	-	-7.3	19.8	-8.9
Mar-93	21.2	-1.3	-	0.2	19.7	-3.2
Apr-93	22.4	5.2	23.0	6.1	24.5	4.7
May-93	49.7	12.3	47.0	13.5	48.9	10.9
Jun-93	103.0	13.8	110.0	15.4	91.2	14.6
Jul-93	79.5	15.1	112.0	17.2	104.9	16.4
Aug-93	69.8	14.9	36.0	15.3	76.7	15.6
Sep-93	22.1	11.1	24.0	11.9	46.3	10.6
Oct-93	12.8	5.9	-	6.6	23.8	5.1
Nov-93	24.3	-3.1	-	-2.9	21.4	-4.2
Dec-93	12.1	-4.3	-	-4.7	26.1	-10.1
Month	Stony Plain		Highvale		Stony Plain (LTN)*	
	Ppt (mm)	Temp (°C)	Ppt (mm)	Temp (°C)	Ppt (mm)	Temp (°C)
Jan-94	60.1	-15.0	-	-15.7	24.5	-12.1
Feb-94	16.7	-16.9	-	-17.6	19.8	-8.9
Mar-94	0.8	1.3	-	0.9	19.7	-3.2
Apr-94	3.8	6.3	0.0	6.1	24.5	4.7
May-94	53.7	11.6	21.0	11.4	48.9	10.9
Jun-94	119.3	14.3	118.0	14.2	91.2	14.6
Jul-94	83.9	17.4	46.0	18.7	104.9	16.4
Aug-94	84.9	16.0	66.0	15.6	76.7	15.6
Sep-94	44.2	13.4	29.0	12.8	46.3	10.6
Oct-94	15.7	5.3	-	3.8	23.8	5.1
Nov-94	18.0	-4.3	-	-6.1	21.4	-4.2
Dec-94	10.5	-9.3	-	-12.7	26.1	-10.1
Month	Stony Plain		Highvale		Stony Plain (LTN)*	
	Ppt (mm)	Temp (°C)	Ppt (mm)	Temp (°C)	Ppt (mm)	Temp (°C)
Jan-95	1.4	-10.1	-	-12.5	24.5	-12.1
Feb-95	10.1	-7.9	-	-8.8	19.8	-8.9
Mar-95	5.0	-3.3	-	-4.1	19.7	-3.2
Apr-95	19.3	3.5	25.0	3	24.5	4.7
May-95	19.6	11.3	23.0	11.2	48.9	10.9
Jun-95	67.0	15.5	76.0	15.1	91.2	14.6
Jul-95			113.0	16.4	104.9	16.4
Aug-95			133.0	12.8	76.7	15.6
Sep-95			8.0	10.6	46.3	10.6

* March 1966 - December 1994 inclusive

Table 3.3. Precipitation (mm) and temperature (°C) for Stony Plain Meteorological Station.

Precipitation	1992-1993	1993-1994	1994-1995	LTN
Overwinter[a]	79.9	114.0	45.0	111.5
April	22.4	3.8	19.3	24.5
Growing Season[b]	336.9	401.7	-	391.8

Temperature	1992-1993	1993-1994	1994-1995	LTN
Overwinter	-7.3	-7.6	-7.0	-7.7
April	5.2	6.3	3.5	4.7
Growing Season	12.2	13.0	-	12.2

[a] - November 1 to March 31 inclusive

[b] - May 1 to September 30 inclusive

Table 3.4. Snow water equivalents (mm) for snowmelt periods 1993, 1994, and 1995.

Sandy Subsoil Watershed

Frame	25-Feb-93	13-Mar-93	2-Mar-94	1-Feb-95	8-Mar-95
SNL1	50	0	97	3% ice	-
SNL2	55	0	111	2% ice	-
SNL3	55	0	113	8% ice	-
SNU1	48	0	115	2% ice	-
SNU2	55	0	108	2% ice	-
SNU3	43	0	105	5% ice	-
SSL1	50	22	83	9	-
SSL2	50	22	97	18	-
SSL3	48	22	103	16	-
SSU1	48	19	92	12	-
SSU2	50	19	81	12	-
SSU3	55	22	113	20	-
Watershed					-
Mean	51	12	102	13	9

West Watershed

	25-Feb-93	13-Mar-93	2-Mar-94	1-Feb-95	8-Mar-95
WSS1	59	26	123	22	-
WSS2	59	26	123	24	-
WSS3	59	26	113	22	-
WSF1	59	19	107	19	-
WSF2	59	19	117	30	-
WSF3	59	19	125	26	-
WNS1	59	16	112	30	-
WNS2	59	16	109	8	-
WNS3	59	16	112	12	-
WNF1	59	16	117	14	-
WNF2	59	16	117	16	-
WNF3	59	16	115	18	-
Watershed Mean	59	16	119	28	15

Table 3.5. Average daily microframe runoff (mm) for the melt 1993, 1994, and 1995.

1993	Sandy Subsoil Watershed		West Watershed	
Date	North-facing	South-facing	North-facing	South-facing
27-Feb	3.9	7.8	0.0	1.2
28-Feb*	-	-	2.5	6.1
1-Mar	15.7	8.8	18.2	15.2
2-Mar	1.0	0.1	12.4	3.9
3-Mar	0.0	0.0	5.3	0.0
4-Mar	0.0	0.0	3.3	0.0
5-Mar	0.0	0.0	3.1	0.0
6-Mar	0.0	0.0	6.7	0.0
7-Mar	0.0	0.0	2.2	0.0
20-Mar	14.0	0.0	4.1	4.1
21-Mar	0.0	0.0	9.4	0.0
22-Mar	0.0	0.0	6.4	0.1
23-Mar	0.0	0.0	0.1	0.0

1994	Sandy Subsoil Watershed		West Watershed	
Date	North-facing	South-facing	North-facing	South-facing
11-Mar	5.2	13.7	0.0	0.0
12-Mar	3.5	9.6	0.0	0.0
13-Mar	25.7	7.6	6.4	11.9
14-Mar	18.6	16.0	3.1	0.0
15-Mar	15.5	15.9	3.3	2.4
16-Mar	12.8	0.6	1.6	0.1
18-Mar	2.2	0.0	2.0	3.2
25-Mar	1.8	0.0	20.7	6.7
26-Mar	0.0	0.0	25.0	3.2
27-Mar	0.0	0.0	24.1	0.0
28-Mar	0.0	0.0	8.8	0.0
30-Mar	0.0	0.0	7.5	0.0

1995	Sandy Subsoil Watershed		West Watershed	
Date	North-facing	South-facing	North-facing	South-facing
1-Feb	1.7	12.3	0.0	0.0
9-Feb	2.0	8.2	0.0	17.0
21-Feb	10.1	10.0	0.0	7.7
22-Feb	9.6	6.5	0.0	5.9
24-Feb	1.8	0.0	0.3	0.0
11-Mar	4.6	10.9	0.3	22.0
12-Mar	9.0	0.4	5.9	18.2
13-Mar	3.4	0.0	2.6	0.2
14-Mar	5.4	0.0	1.7	0.0
15-Mar	7.7	0.0	5.0	0.4
16-Mar	4.4	0.0	1.3	0.0

- February 28, 1993 Sandy Subsoil Watershed hillslope flow added to March 1 values.

Table 3.6. Microframe runoff water quality.

Watershed	Total Suspended Solids (mg/L)			pH			Electrical Conductivity (dS/m)		
Sandy Subsoil	Mean	Std. Dev	Range	Mean	Std. Dev	Range	Mean	Std. Dev	Range
Summer 1993 n=61	188	147	48 - 845	6.6	0.3	6.2-7.5	0.09	0.06	0.02 - 0.3
Summer 1994 n=16	73	68	13 - 275	6.4	0.32	5.9-6.8	0.03	0.01	0.01 - 0.05
Snowmelt 1993 n=31	117	52	34 - 225	6.4	0.5	5.8-8.0	0.08	0.03	0.05 - 0.13
Snowmelt 1994 n=48	18	8.6	9 - 36	6.8	0.2	6.4-7.2	0.09	0.08	0.03 - 0.52
Snowmelt 1995 n=49	13	13	0 - 55	6.6	0.3	6.0 - 7.3	0.03	0.01	0.01 - 0.06
West									
Summer 1993 n=22	140	103	32 - 394	6.7	0.3	6.1-7.5	0.12	0.14	0.03-0.61
Summer 1994 n=2	40	6	36 - 45	6.0	0.03	5.9-6.0	0.48	0.1	0.55-0.4
Snowmelt 1993 n=51	94	74	22 - 393	6.5	0.8	5.9-8.2	0.11	0.06	0.04-0.20
Snowmelt 1994 n=58	16	8	6 - 37	6.8	0.2	6.4-7.2	0.09	0.05	0.03-0.23
Snowmelt 1995 n=20	8	10	0 - 38	6.5	0.2	6.2 - 6.9	0.02	0.01	0.01 - 0.04

Table 3.7. Watershed snowmelt runoff quality in 1993

Sandy Subsoil Watershed[a]	Sediment (mg/L)	pH	EC (dS/m)	NO_3 (ppm)	NH_4 (ppm)	PO_4 (ppm)
Average	n/a	6.4	0.05	0.11	0.55	0.08
Std. Dev.	n/a	0.13	0.02	0.08	0.25	0.09
Std. Error	n/a	0.03	0.004	0.04	0.11	0.04
Maximum	n/a	6.6	0.07	0.24	0.88	0.19
Minimum	n/a	6.2	0.03	0.03	0.28	0.01

West Watershed[b]	Sediment (mg/L)	pH	EC (dS/m)	NO_3 (ppm)	NH_4 (ppm)	PO_4 (ppm)
Average	85	6.5	0.06	0.38	0.31	0.06
Std. Dev.	52	0.25	0.03	0.23	0.17	0.03
Std. Error	8	0.02	0.002	0.10	0.08	0.01
Maximum	269	6.9	0.12	0.88	0.62	0.12
Minimum	35	6.1	0.03	0.14	0.01	0.01

a - n = 5 for all parameters

b - n = 45 for sediment; n = 12 for all other parameters

Table 3.8. Watershed snowmelt runoff quality in 1994.

Sandy Subsoil Watershed[a]	Sediment (mg/L)	pH	EC (dS/m)	NO_3 (ppm)	NH_4 (ppm)	PO_4 (ppm)
Average	6	6.7	0.07	0.41	1.16	0.07
Std. Dev.	5	0.2	0.03	0.44	0.58	0.08
Std. Error	2	0.04	0.01	0.13	0.18	0.02
Maximum	10	7.0	0.12	1.31	2.15	0.22
Minimum	0	6.5	0.04	0.00	0.56	0.00

West Watershed[b]	Sediment (mg/L)	pH	EC (dS/m)	NO_3 (ppm)	NH_4 (ppm)	PO_4 (ppm)
Average	7	6.8	0.07	0.28	0.46	0.30
Std. Dev.	5	0.3	0.03	0.34	0.34	0.27
Std. Error	1	0.1	0.01	0.10	0.10	0.08
Maximum	12	7.2	0.13	0.91	1.28	0.87
Minimum	0	6.4	0.04	0.00	0.18	0.08

[a] n = 11 for all parameters

[b] n = 12 for all parameters

Table 3.9. Watershed snowmelt runoff quality in 1995.

Sandy Subsoil Watershed[a]	Sediment (mg/L)	pH	EC (dS/m)	NO_3 (ppm)	NH_4 (ppm)	PO_4 (ppm)
Average	2	6.7	0.03	0.31	0.72	0.13
Std. Dev.	0.5	0.2	0.01	0.38	0.31	0.06
Std. Error	0.3	0.1	0.00	0.17	0.14	0.03
Maximum	2	6.9	0.04	0.94	1.20	0.20
Minimum	1	6.3	0.02	0.01	0.45	0.04

West Watershed[b]	Sediment (mg/L)	pH	EC (dS/m)	NO_3 (ppm)	NH_4 (ppm)	PO_4 (ppm)
Average	1	6.5	0.02	0.09	0.52	0.39
Std. Dev.	1	0.3	0.01	0.14	0.17	0.16
Std. Error	0.3	0.1	0.00	0.04	0.05	0.05
Maximum	3	7.0	0.04	0.38	0.84	0.62
Minimum	0	6.3	0.02	0.01	0.27	0.18

[a] n = 5 for all parameters

[b] n = 10 for all parameters

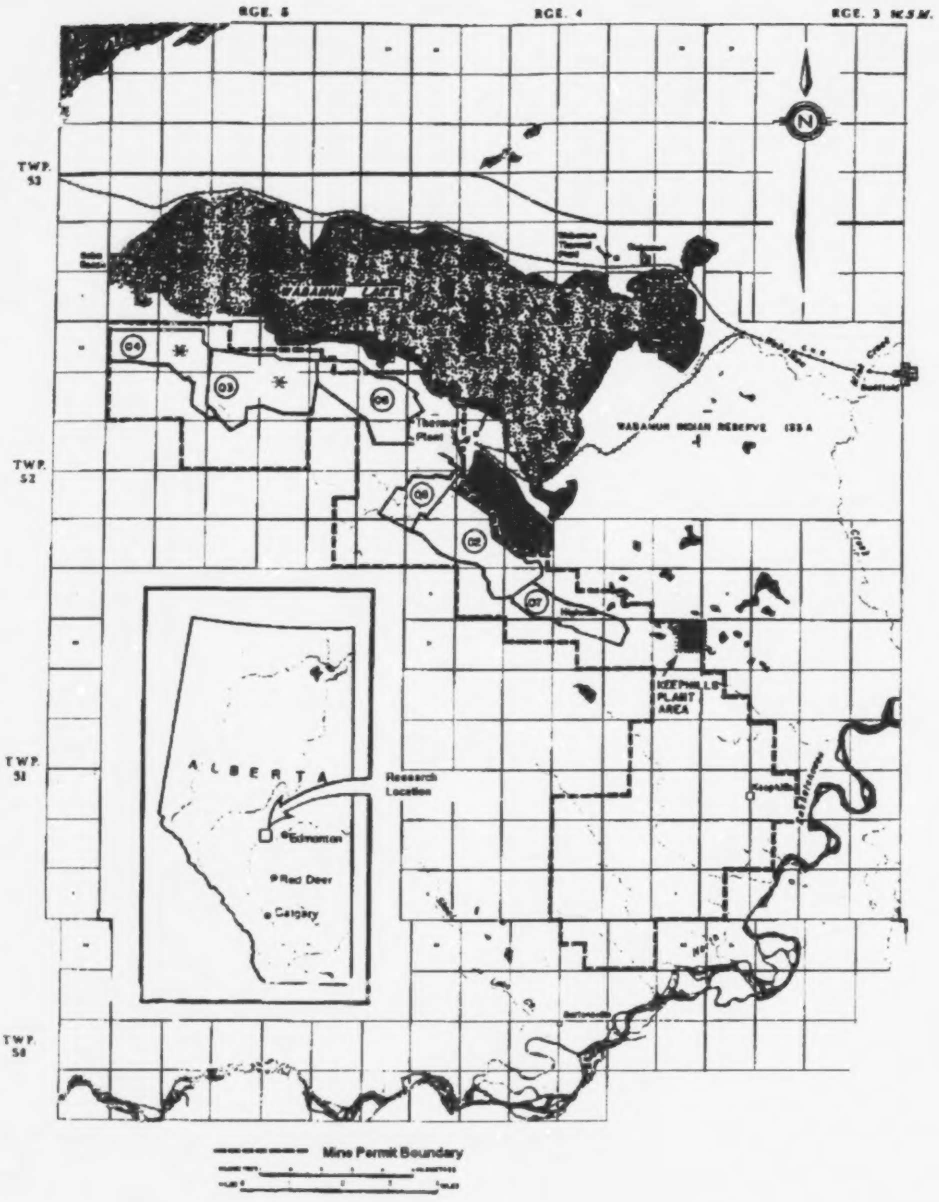
Table 3.10. Water quality guidelines and water quality of streams draining into Lake Wabamun.

	pH	Total N (ppm)	Total P (ppm)
Alberta Surface Water Quality Objectives (Habgood, 1983)	6.5-8.5	<1.0	<0.15

	pH	NO_3 (ppm)	NH_4 (ppm)
Canadian Water Quality Guidelines (1995)	6.5-9.0	Concentrations that stimulate weed growth should be avoided.	<2.2

		Total N (ppm)	Total P (ppm)
Alberta Environmental Protection (1985)[a]	-	0.89-2.24	0.094-0.321

[a] - concentrations of nitrogen and phosphorous for streams draining into Lake Wabamun.


RGE. 5
RGE. 4
RGE. 3 W.5 M.
TWP. 53
TWP. 52
TWP. 51
TWP. 50
N
WABAMUN LAKE
04
03
06
08
02
07
Thermal Plant
WABAMUN INDIAN RESERVE 133 A
KEEPHILLS PLANT AREA
ALBERTA
Research Location
Edmonton
Red Deer
Calgary
Mine Permit Boundary

* - location of watersheds

④ - refers to Pit 04

Figure 3.1. Map of the TransAlta Utilities Highvale Mine.
(adapted from Monenco Consultants)

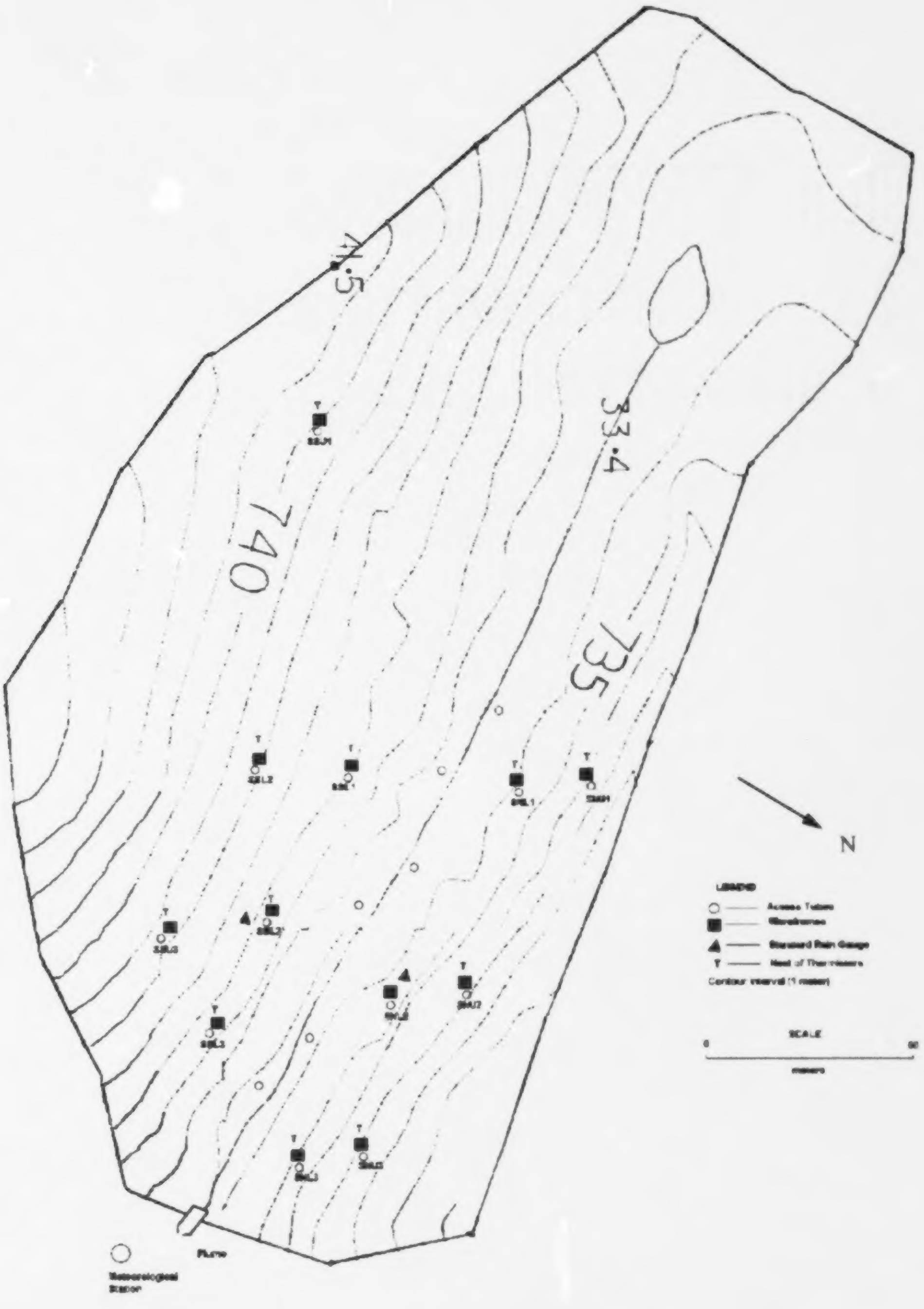

741.5
740
733.4
735
N
LEGEND
Access Tubes
Standard Rain Gauge
Nest of Thermistors
Contour interval (1 meter)
SCALE
0
meters
Flume
Meteorological Station

Figure 3.2. Topographic map of the Sandy Subsoil Watershed.
(adapted from TransAlta Utilities 1359 pb0501)

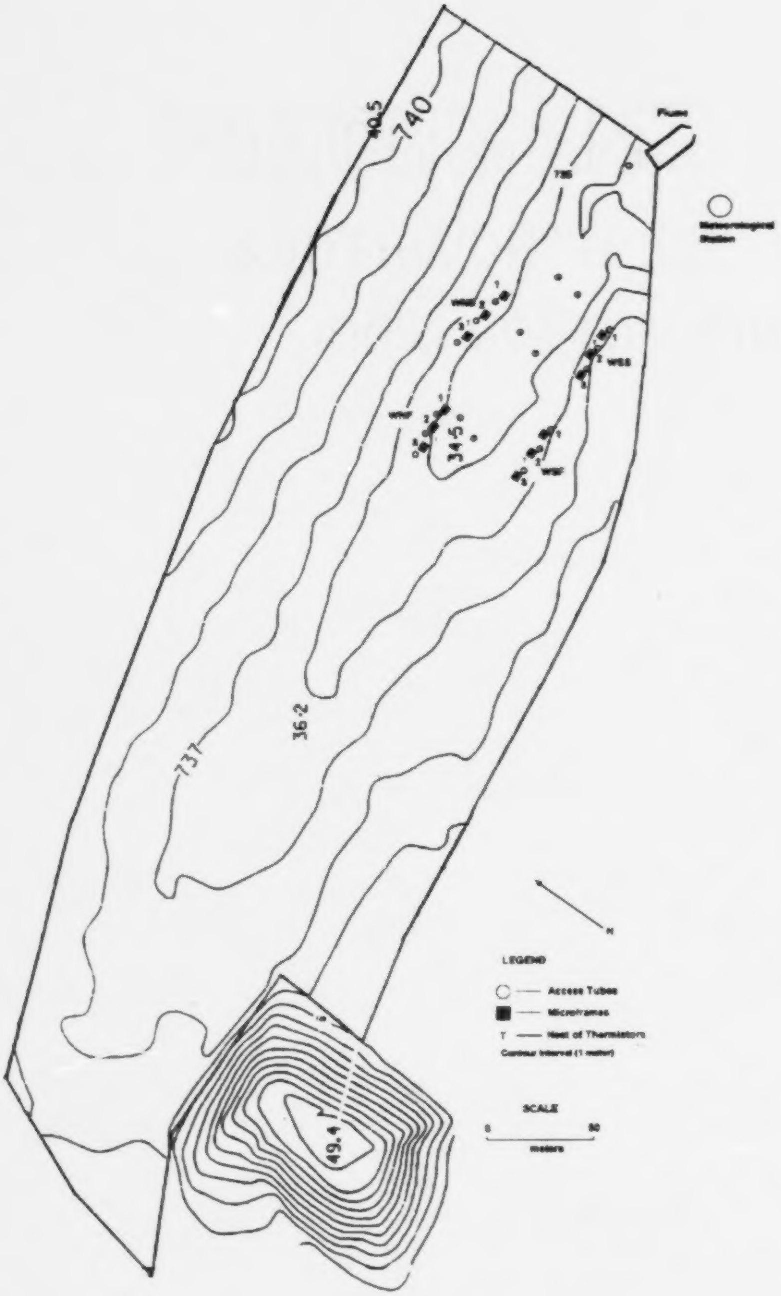

40.5
740
Flume
Meteorological Station
WSS
34.5
36.2
737
N
49.4
LEGEND
○ —— Access Tubes
■ —— Microframes
T —— Nest of Thermistors
Contour Interval (1 meter)
SCALE
0
50
meters

Figure 3.3. Topographic map of the West Watershed.
(adapted from TransAlta Utilities topographic map)

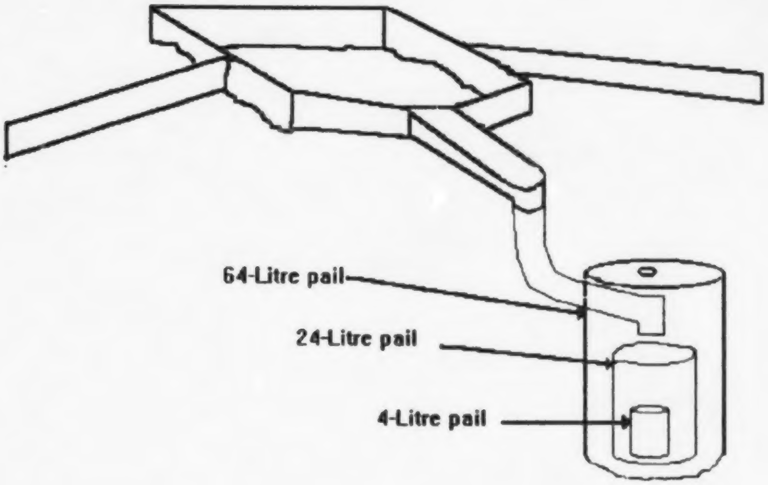

64-Litre pail
24-Litre pail
4-Litre pail

Figure 3.4. Schematic diagram of hillslope microframes.

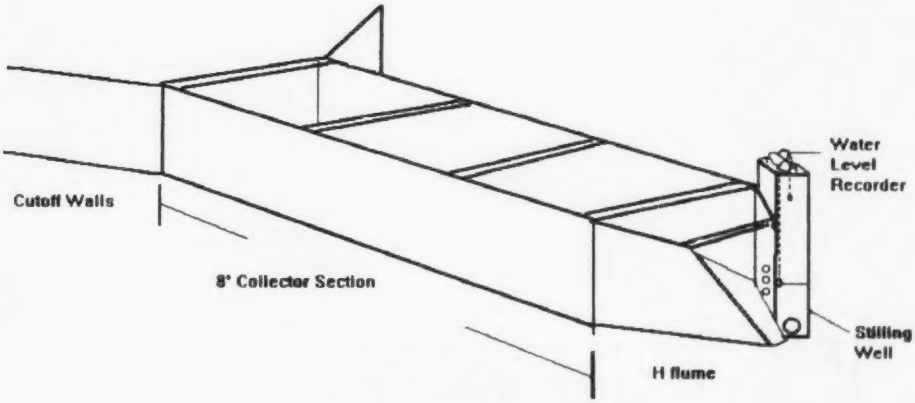

Water
Level
Recorder
Cutoff Walls
8' Collector Section
Stilling
Well
H flume

Figure 3.5. Schematic diagram of 2' H-flume.

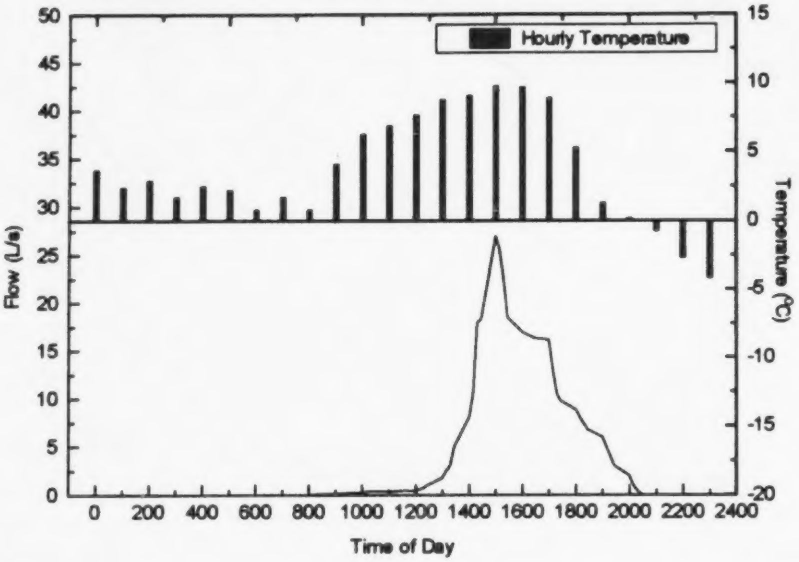


Figure 3.6. Termination of the recession limb using air temperature for the March 2, 1993 hydrograph for the West Watershed. (Last manual reading taken at 18.45 h).

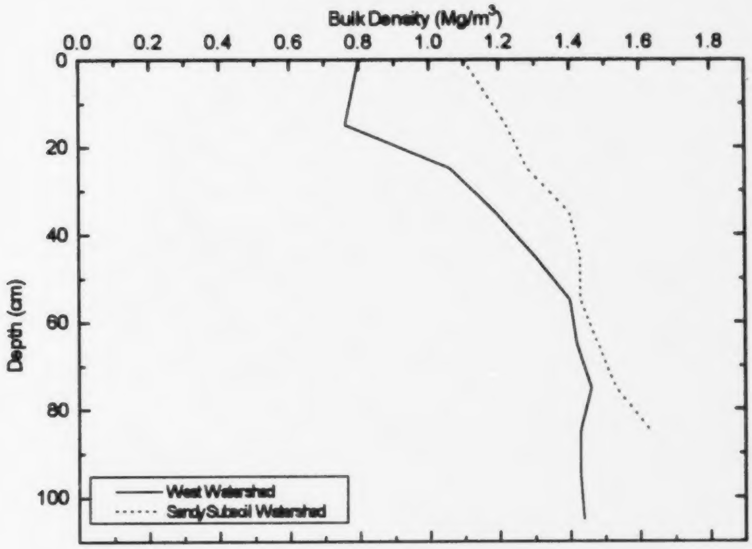


Figure 3.7. Average bulk density profiles for both watersheds in May, 1993.

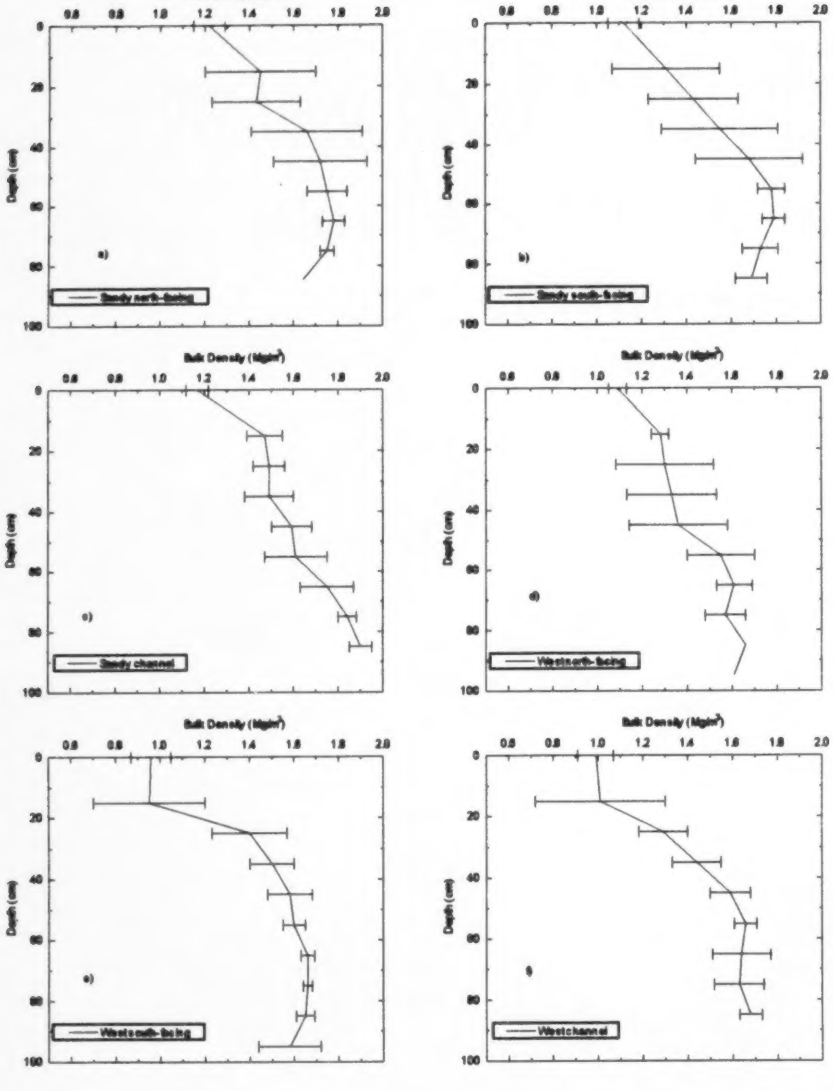
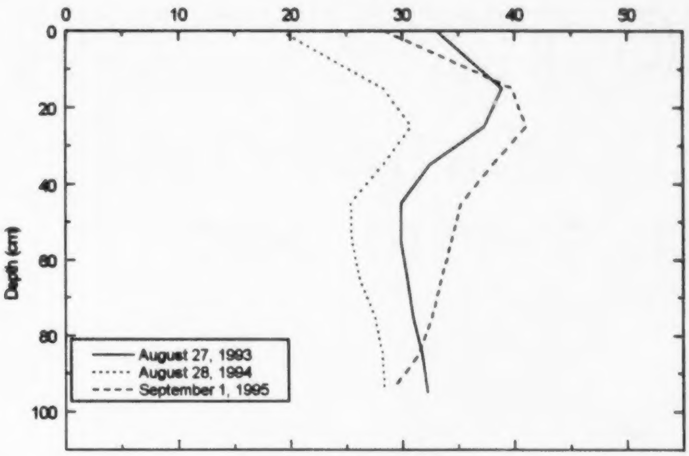
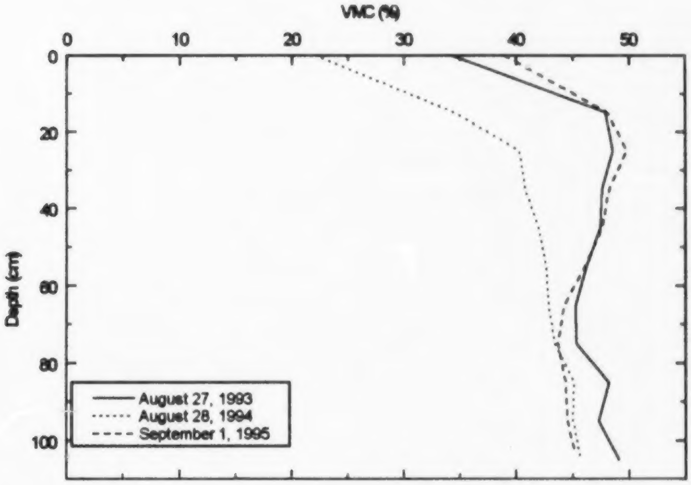


Figure 3.8. Average bulk density profiles for both aspects and the channel within the Sandy Subsoil and West Watersheds.

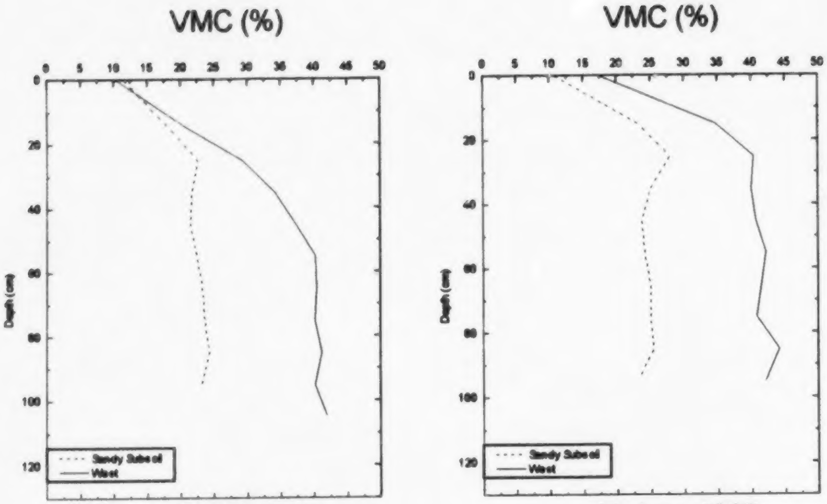


a) Sandy Subsoil Watershed



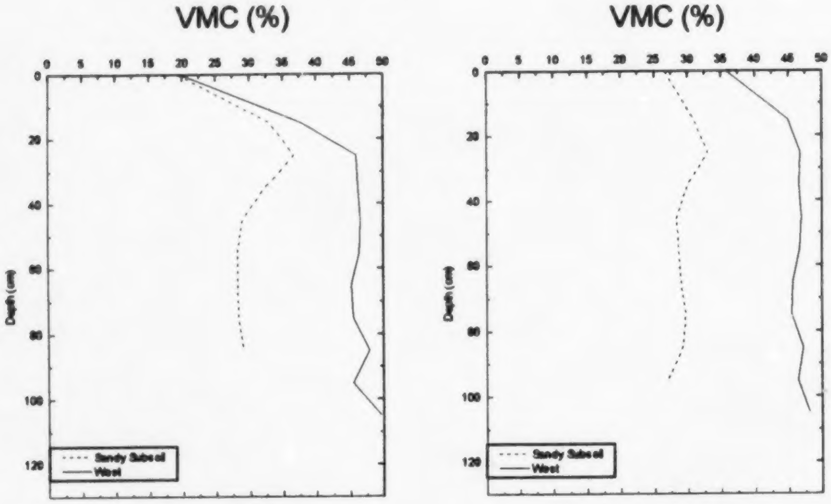
b) West Watershed

Figure 3.9. Volumetric soil moisture (VMC) profiles at the end of August 1993, 1994, and 1995 in a) Sandy Subsoil Watershed and b) West Watershed.



a) May 1993

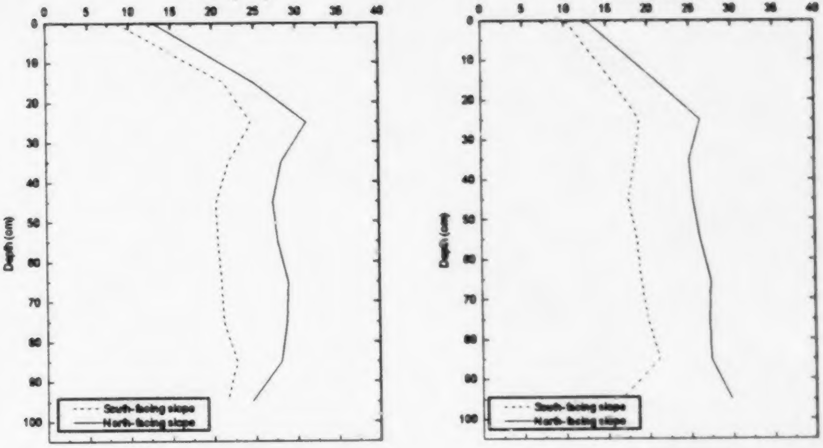
b) June 1993



c) July 1993

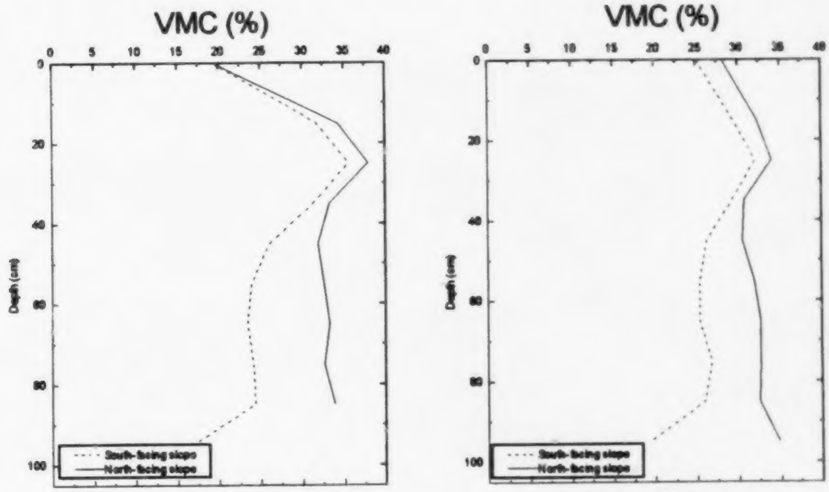
d) August 1993

Figure 3.10. Average volumetric soil moisture profiles (VMC) for the two watersheds in (a) May, (b) June, (c) July, and (d) August, 1993.



a) May 4/93

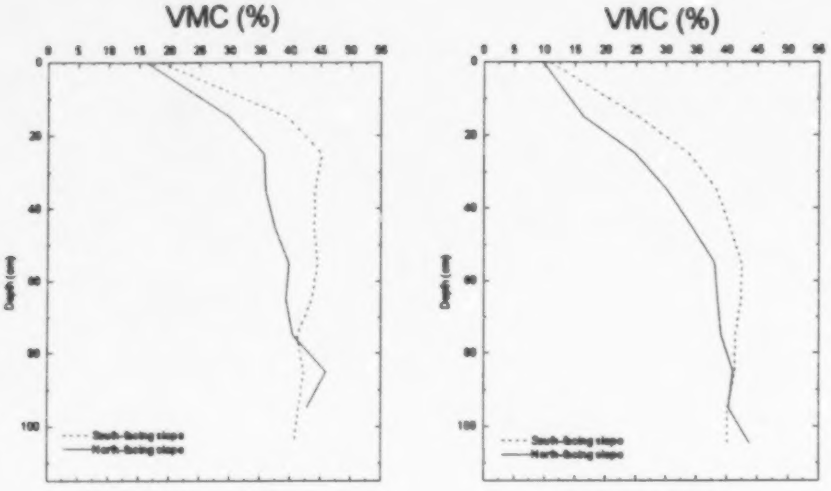
b) June 7/93



c) July 12/93

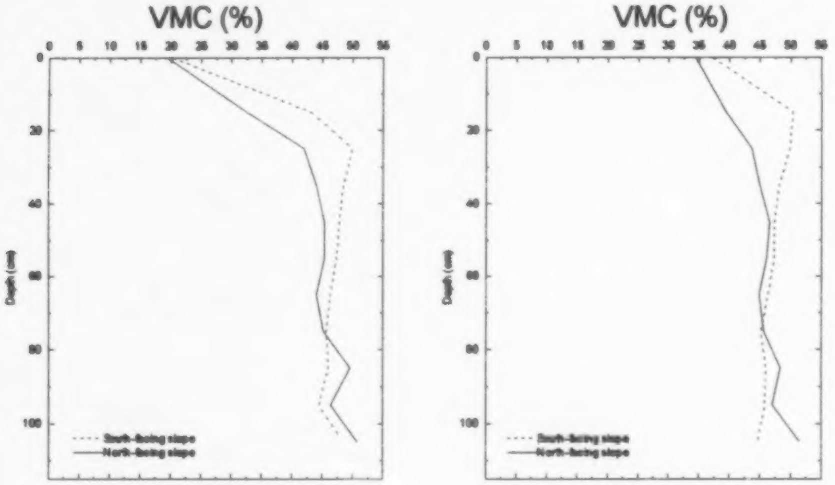
d) August 16/93

Figure 3.11. Soil moisture profiles for the south- and north-facing slopes in the Sandy Subsoil Watershed on (a) May 4, (b) June 7, (c) July 12, and (d) August 16, 1993.



a) May 4/93

b) June 7/93



c) July 12/93

d) August 16/93

Figure 3.12. Soil moisture profiles for the south- and north-facing slopes in the West Watershed on (a) May 4, (b) June 7, (c) July 12, and (d) August 16, 1993.

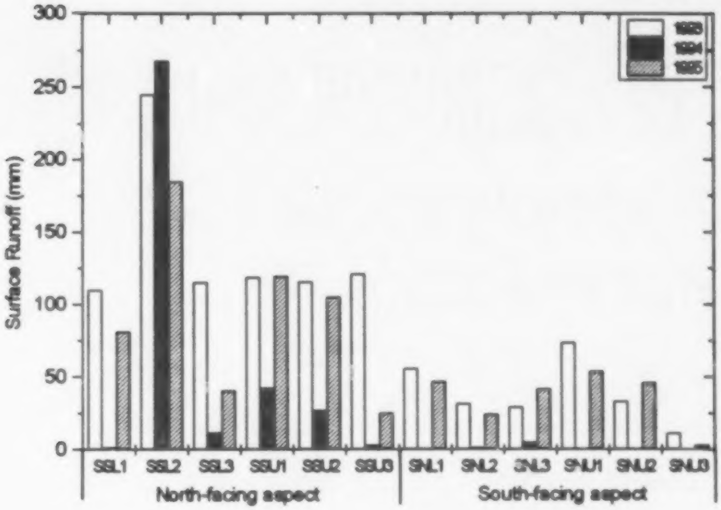


Figure 3.13. Total microframe runoff for 1993, 1994 and 1995 rainfall events in the Sandy Subsoil Watershed. (U - upper slope location; L - lower slope location)

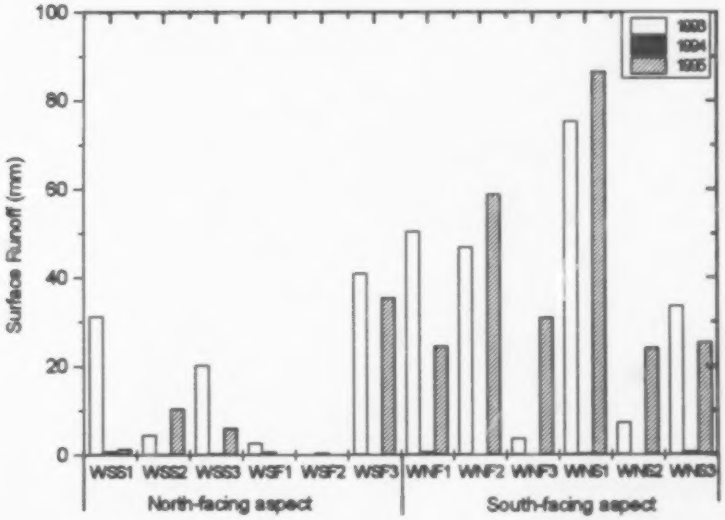


Figure 3.14. Total microframe runoff for 1993, 1994 and 1995 rainfall events in the West Watershed. (S - located on steep slope (13%); F - located on flat slope 5%))

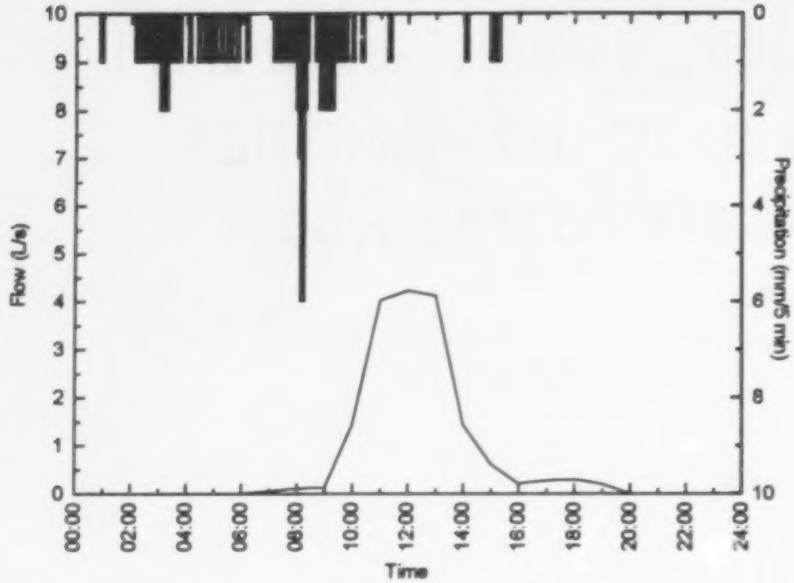


Figure 3.15. Flow from the Sandy Subsoil Watershed on July 21,1993.

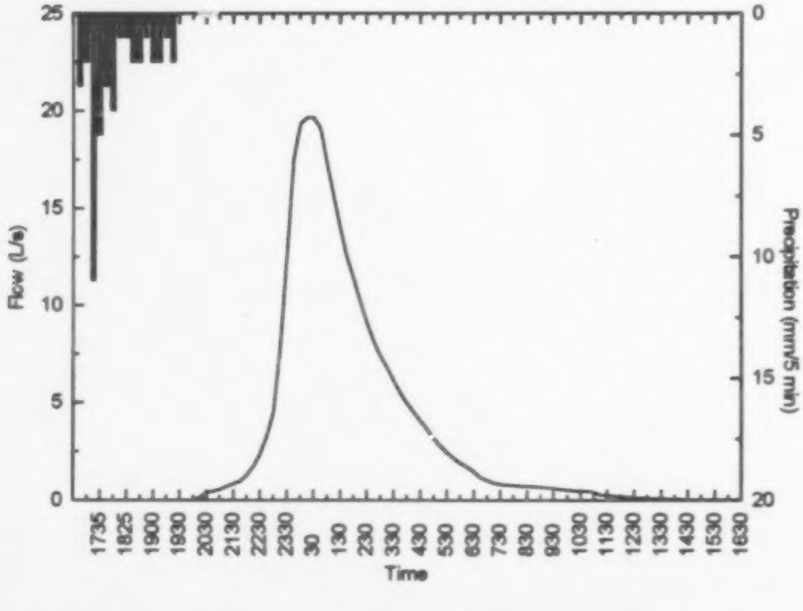


Figure 3.16. Flow from the Sandy Subsoil Watershed on August 16-17, 1995.

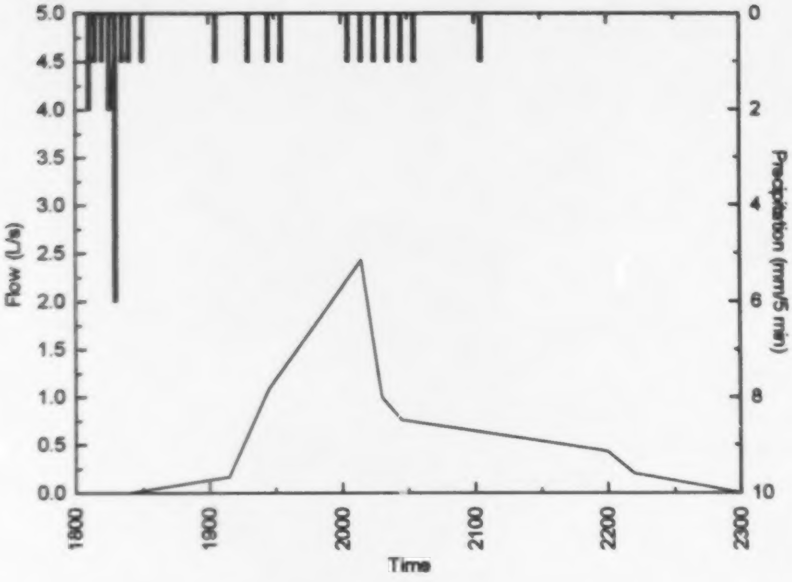


Figure 3.17. Flow from the West Watershed on June 27,1993.

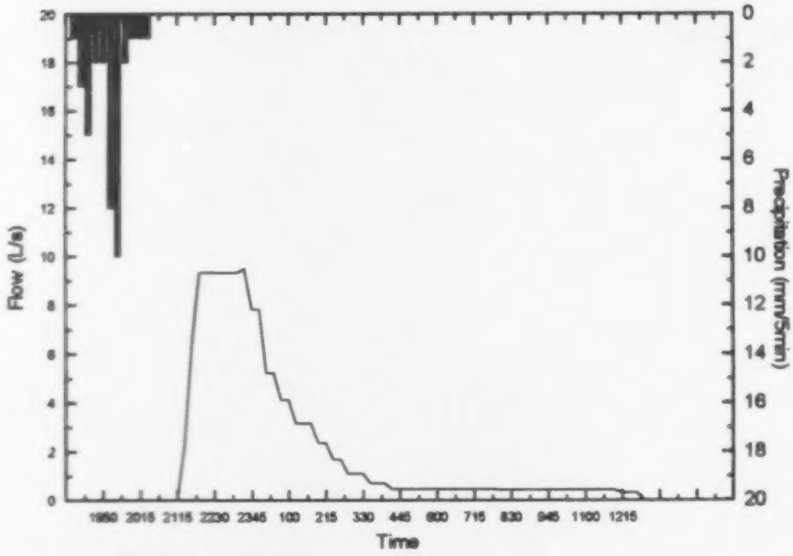


Figure 3.18. Flow from the West Watershed on July 25, 1995.

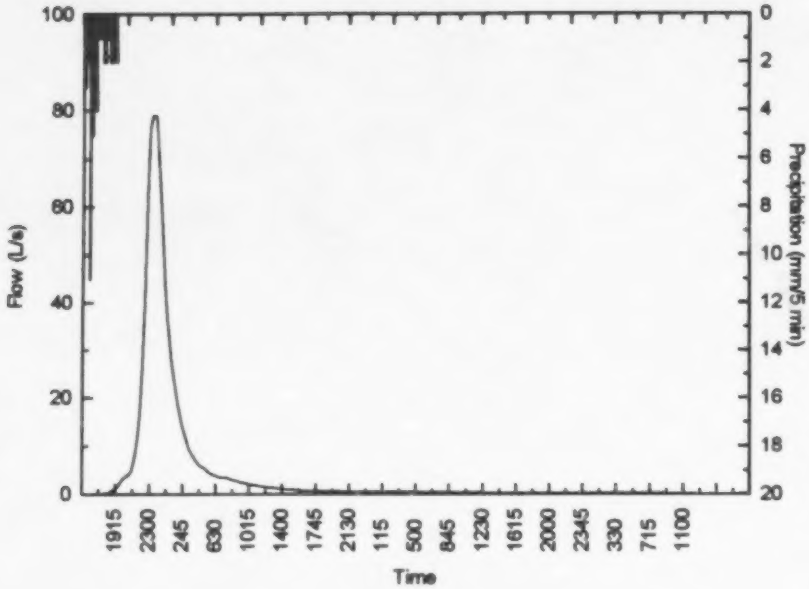


Figure 3.19. Flow from the West Watershed for August 16, 1995 rainfall event.

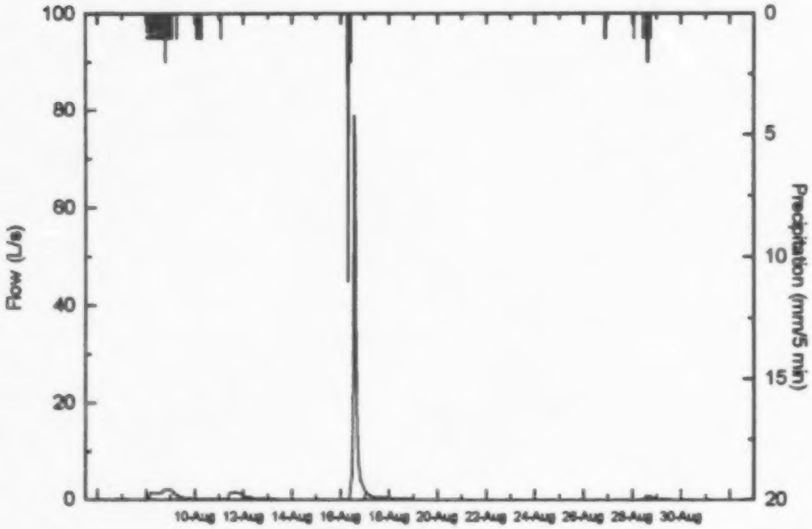


Figure 3.20. Flow from the West Watershed in August 1995.

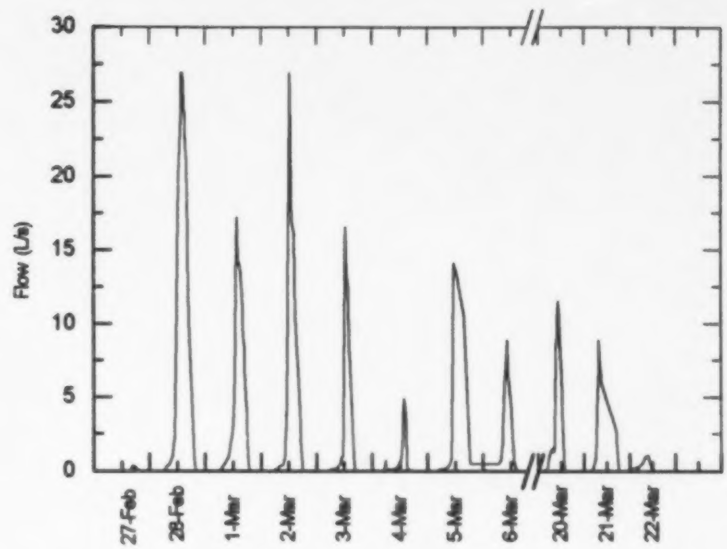


Figure 3.21. Daily snowmelt hydrographs for the West Watershed in 1993.

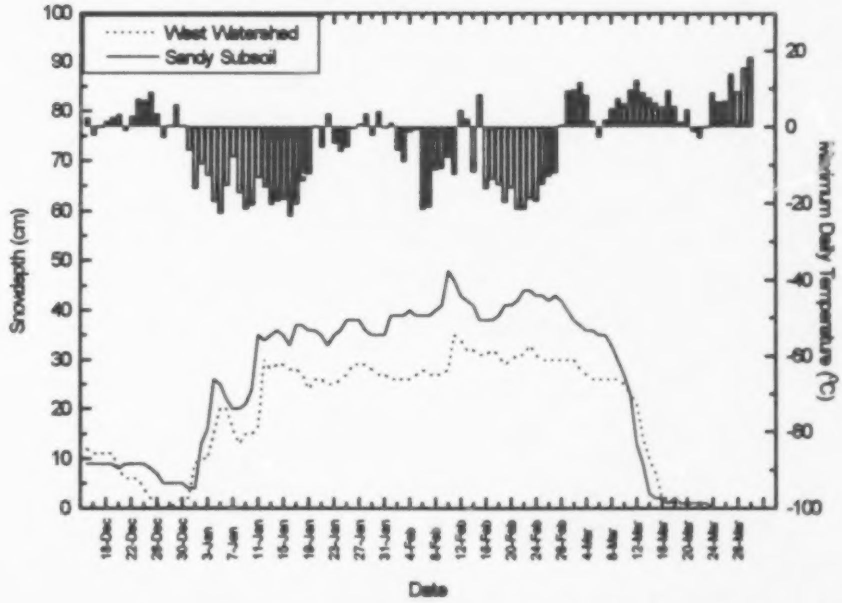


Figure 3.22. Snow accumulation for both watersheds; December 1993 - March 1994.

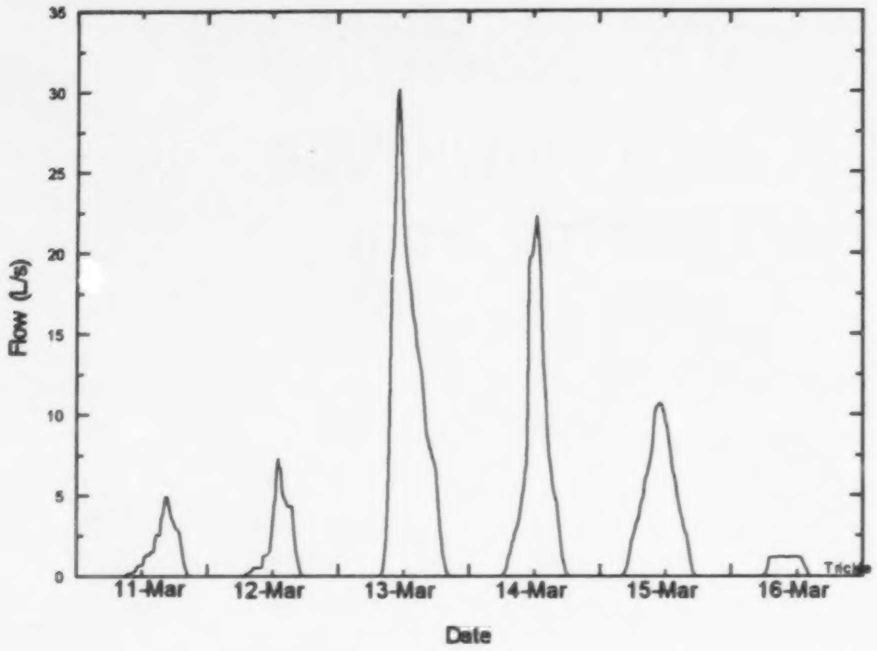


Figure 3.23. Daily snowmelt hydrographs for the Sandy Subsoil Watershed in 1994.

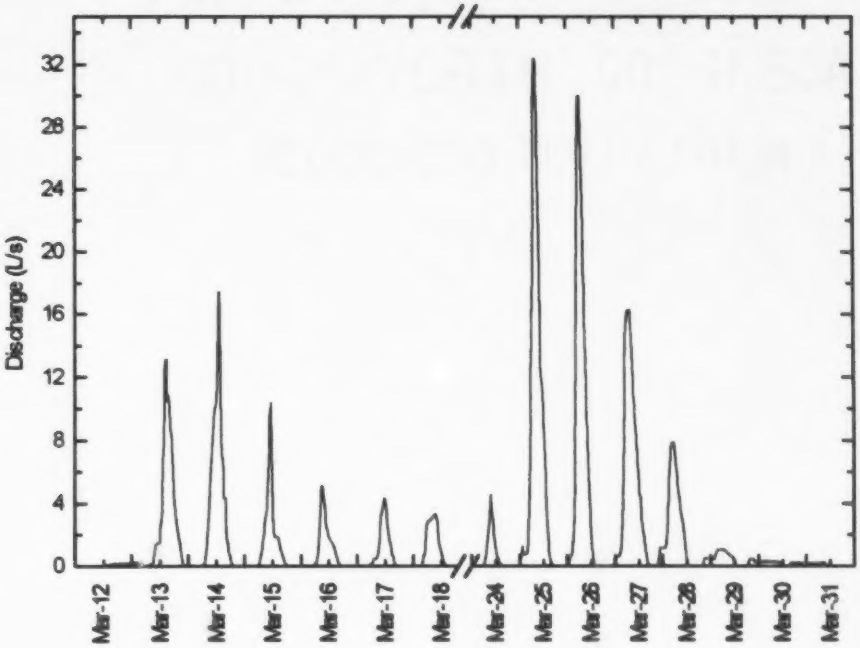


Figure 3.24. Daily snowmelt hydrographs for the West Watershed in 1994.

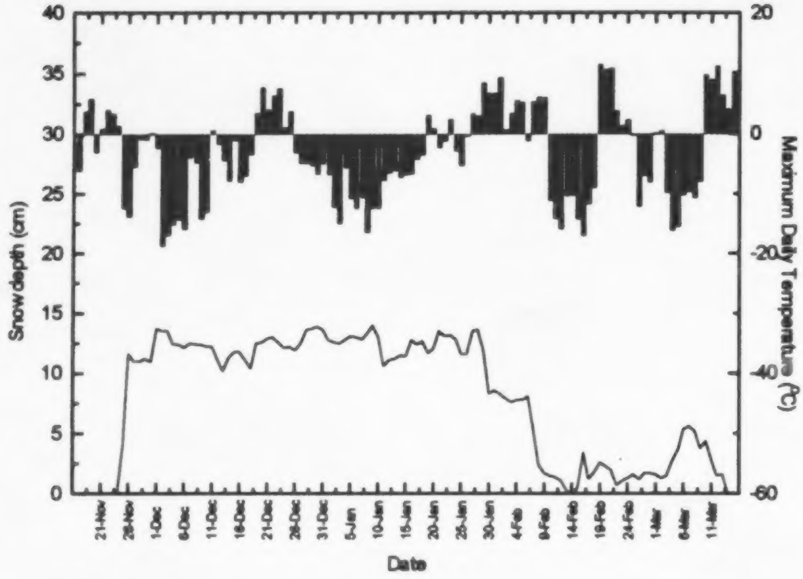


Figure 3.25. Snow accumulation for West Watershed; November 1994 - March 1995.

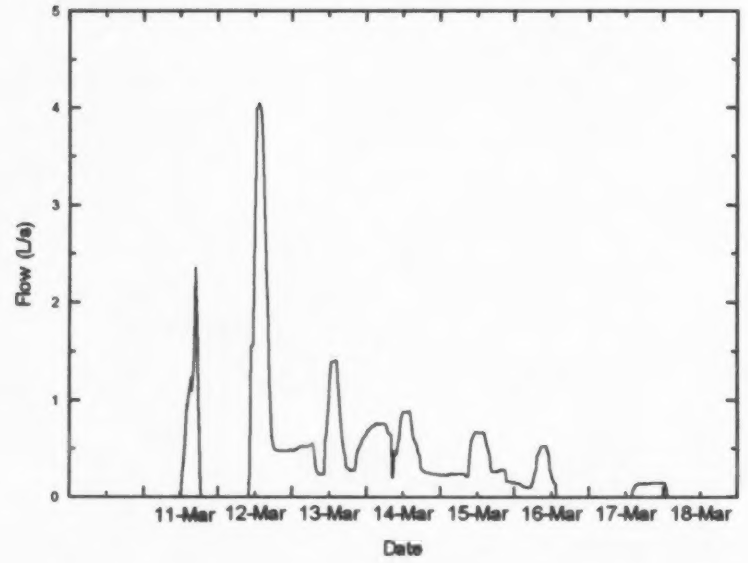


Figure 3.26. Daily snowmelt hydrographs for the Sandy Subsoil Watershed in 1995.

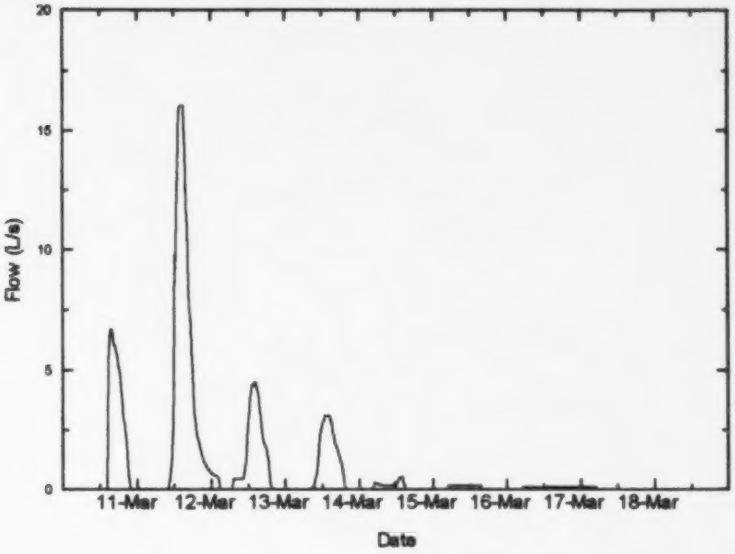


Figure 3.27. Daily snowmelt hydrographs for the West Watershed in 1995.

4. THE INFLUENCE OF SCALE ON SURFACE RUNOFF FROM RECLAIMED SURFACE MINED WATERSHEDS

4.1. INTRODUCTION

Determining surface flow phenomena from small plot or frame studies is critical to quantifying surface flow processes. Many of the external factors that add complexity to rainfall-runoff relationships at the hillslope or watershed scale can be controlled or minimized within a small plot (Mathier et al., 1989). Small scale plot studies are valuable for identifying, quantifying and explaining factors that determine overland flow and runoff mechanisms (Abrahams and Parsons, 1990; Dunne et al., 1991; Meek et al., 1992). Small scale plot studies successfully described infiltration characteristics and erosion processes on reclaimed land after surface mining (Gilley et al., 1977; Schroeder, 1987; Schroeder, 1989; Jorgensen and Gardner, 1987; Bonta et al., 1991; Olyphant et al., 1991; McIntosh and Barnhisel, 1993). Snowmelt processes are also well described and studied at the plot scale to ascertain the influence of soil moisture on snowmelt runoff (Kane and Stein, 1984), to quantify the distribution of snow-water during the melt period (Kane et al., 1991) and to determine the timing and volumes of snowmelt runoff for different cropping practices (Chanasyk and Woytowich, 1986).

Results from small scale plot studies are often used as input for predicting runoff from larger scale catchments with the hope that the surface flow response of the catchment can be predicted as an additive accumulation of individual hillslope flow responses from defined elements or areas within the catchment (Amerman and McGuinness, 1967; Anderson and Burt, 1990). Physically-based distributed-parameter models are structured on this premise (Beasley et al., 1980).

Runoff from a catchment has been described as an integration of two interrelated subsystems: the hillslopes produce runoff and channel networks transport water to the outlet (Rodriquez-Iturbe, 1985). Dominant processes that determine surface flow on a hillslope may not be the same processes that determine flow from a catchment (Klemes, 1983; Kane et al., 1991). Researchers in hydrology and overland flow hydraulics stipulate that results from small plot studies should be only used as limited approximations of larger scale systems (Scoging et al., 1992), as runoff mechanisms vary for different areas within a heterogeneous catchment (Allan and Roulet, 1994). Local hillslope processes are attenuated when the spatial scale is increased (Wood et al., 1988).

Newly reclaimed surface-mined catchments lack the profile heterogeneity of many natural catchments due to the nature of the reclamation procedure. The contoured and smoothed spoil material is covered with a fairly uniform depth of subsoil and topsoil. Infiltration into the newly reclaimed watersheds is generally low and surface runoff is generally dominated by infiltration-excess overland flow (Guebert and Gardner, 1991). Surface flow response from these reconstructed catchments should be fairly uniform over the catchment area, and relatively easy to predict from hillslope runoff plots. As an example, Ritter (1991) used plot infiltration data to parameterize the ANSWERS model for hydrologic simulation at the catchment scale on two reclaimed catchments in central Pennsylvania; with reasonable success.

The ratio of surface runoff from an area (output) to total precipitation into an area (input) over a designated period of time is termed 'runoff coefficient' (Singh, 1992). Runoff coefficients are temporally variable and indicative of the amount of losses (soil and depression storage, interception) occurring within an area on an event, seasonal or annual basis (Dingman, 1994). Runoff coefficients are spatially variable, reflecting the infiltration characteristics of the landscape surface (Allan and Roulet, 1994). Runoff coefficients are commonly used when determining design criteria for hydraulic structures or conveyance channels (Hall, 1984), or when comparing the hydrologic response of a defined contributing area to various precipitation events (Dingman, 1994). Rainfall runoff coefficients as high as 0.50 have been reported for surface-mined reclaimed catchments in central Pennsylvania (Ritter, 1990).

The problem of extrapolating results at the plot scale to the watershed or basin scale is a topic of much recent discussion and research (Blösch and Sivapalan, 1995). Unlike the artificial boundaries imposed by plot or frame scale studies, Klemes (1983) wrote "... we cannot impose scales but have to search for those that exist and try to understand their interrelationships and patterns."

A research project was initiated in 1992 to determine the influence of scale on surface runoff from reclaimed surface-mined catchments in central Alberta. It was hypothesized that for these watersheds, runoff volume and timing on a watershed scale could be reasonably estimated from hillslope runoff plots distributed throughout the watershed. Runoff coefficients calculated for hillslope microframes would be the same or similar to those calculated for flow from the watershed for both snowmelt and summer rainfall events.

4.2. STUDY AREA

Refer to Chapter 3 for a description of the study area and for the Materials and Methods section.

4.2.1. General

In addition to description in Chapter 3, long-term rainfall data from the Edmonton International Airport located approximately 90 km east of the study sites, were used to compile the Depth/Duration/Frequency graphs used in the analysis.

4.2.2. Procedure

Surface runoff was measured during summer rainstorm and spring snowmelt events at both the hillslope scale and the entire catchment scale starting with snowmelt 1993 and continuing to the end of summer 1995.

The volume of runoff contained in the collection buckets was measured immediately following each rainfall event, and at least twice daily during springmelt. A rainfall event was defined as any continuous period with 5 mm or greater of total rainfall.

The 2 ft. H-flumes were manually calibrated during snowmelt 1993 and the resultant stage-discharge curve compared favorably to published stage-discharge relationships for 2 ft. H-flumes (USDA, 1979). The published stage-discharge tables were used for determining subsequent catchment discharge volumes.

Snow core samples for depth and water equivalent were obtained adjacent to each of the hillslope microframes, and at 40 locations within the catchment, prior to snowmelt events of each of the study years. A snowmelt event is defined as occurring if surface runoff commences from the hillslope microframes but not necessarily from the watershed.

Comparisons were made between runoff coefficients at the hillslope scale to runoff coefficients from the watershed for each reclaimed watershed separately. Runoff coefficients from microframe runoff data were calculated by averaging frame runoff (mm) for a given event, subtracting channel storage and dividing by total precipitation. Watershed runoff coefficients were calculated as the ratio of total runoff minus channel storage divided by total precipitation.

To examine rainfall/runoff relationships for the hillslope microframes, rainfall amounts for individual storms were compared to the runoff coefficients for those storms.

4.3. RESULTS

4.3.1. Meteorology

See Chapter 3 for general description.

Of 54 rainfall events in three years of monitoring, only 7 had return periods greater than 2 years (Figure 4.1): 3 in 1993, 2 in 1994 and 2 in 1995. There were a few notable rainfall events with large 5-min peak intensities; in 1993, 77 mm of rainfall fell in under 19 hours and peak 5-min rainfall intensity reached 72 mm h^{-1}. One event in 1993 with a peak 5-min intensity of 84 mm h^{-1} resulted in only 15 mm of rainfall in under 1 h. Two notable events of 1995 were: July 25 when 36 mm of rain fell in 2 h 45 min with peak 5-min intensity of 120 mm h^{-1} and August 16 when 44 mm of rain fell in over 2 h with peak 5-min intensity of 132 mm h^{-1} (Tables 4.1, 4.2, and 4.3).

4.3.2. Summer Surface Runoff

Comparison of runoff coefficients for hillslopes and watersheds for summer rainfall events did not show any consistent relationships. The hillslopes of the Sandy Subsoil Watershed produced overland flow for most summer rainfall events and often all monitored sections of the hillslopes contributed overland flow, but the watershed responded to only one rainfall event in each of 1993 and 1995. Overland flow from the hillslopes of the West Watershed occurred less frequently and uniformly than that from the Sandy Subsoil Watershed, but watershed runoff occurred during eight summer rainfall events in three years of monitoring.

Ten rainfall events during summer 1993 resulted in surface runoff from the microframes within the Sandy Subsoil catchment; eight rainfall events resulted in runoff within the West Watershed (Table 4.1). Runoff coefficients from the microframes ranged from less than 0.01 to 0.44 for the Sandy Subsoil and 0.01 to 0.29 for the West Watershed. Within the Sandy Subsoil Watershed, highest runoff coefficients resulted when the combination of rainfall volume and rainfall intensity was greatest, and most or all hillslope frames contributed surface runoff. Only once (July 21) did surface runoff occur from all twelve frames located within the West Watershed. A few frames contributed the majority of surface runoff during rainfall in 1993.

In contrast to the microframes, only one rainfall event on July 21,1993 initiated watershed flow from the Sandy Subsoil Watershed (Table 4.1). All the hillslope areas contributed surface runoff during this rainfall event. However, the runoff coefficient calculated from the hillslope microframe runoff was 0.44, while that from the watershed was only 0.02. Three 1993 rainfall events initiated watershed flow from the West Watershed. The highest runoff coefficient (0.03) occurred July 21. Watershed surface discharge occurred during two other lesser events but runoff coefficients were very low.

In 1994, runoff coefficients from hillslope microframes ranged from 0.01 to 0.35 for the Sandy Subsoil Watershed (Table 4.2). Generally, the higher the combination of rainfall intensity and amount, the higher the runoff coefficient. Exceptions occurred when antecedent rainfall occurred a day or two previous to the event that resulted in higher runoff coefficients (for example July 2 and 3 and August 7 and 9), and later in the fall. Hillslope runoff coefficients ranged from 0.01 to 0.03 for the West Watershed in 1994. There was no watershed flow during rainfall events from either watershed in 1994.

Hillslope overland flow from the Sandy Subsoil Watershed occurred during 15 rainfall events in 1995 (Table 4.3) with runoff coefficients ranging from 0.01 to 0.71.

Consistent with previous years, the high runoff coefficients coincided with rainfall events with the highest combination of rainfall intensity and amount. The highest runoff coefficient (0.71) was for the July 25, 1995 rainfall event. Vegetation within the hillslope microframes was clipped July 23, two days prior to this rainfall which could explain the high runoff coefficient. Depressions along the channel partially filled after the July 25 rainstorm for the first time during the summer in the three years of monitoring. Runoff from the Sandy Subsoil Watershed occurred only once during summer 1995 with a runoff coefficient of 0.19, less than half that of the hillslope microframes (0.43).

Overland flow occurred during 6 rainfall events from the hillslope frames in the West Watershed in summer 1995 (Table 4.3). Runoff coefficients ranged from 0.01 to 0.43. Overland flow from all 12 hillslope frames did not occur. Even for the fairly extreme rainfall event on August 16, overland flow occurred from only 6 hillslope frames.

Discharge from the West Watershed occurred five times during summer 1995 with runoff coefficients ranging from 0.01 to 0.26. Runoff coefficients were less than those for hillslope frames for three of the events, but for two lesser storms, on August 11 and 29, runoff coefficients were higher for watershed than hillslope frames.

4.3.3. Surface Runoff Initiation

No clear pattern between rainfall amount and runoff coefficients was evident (relationship for the Sandy Subsoil Watershed shown in Figure 4.2), consistent with findings reported in other studies (Naef, 1985). To incorporate rainfall intensities into the calculation seemed a logical next step considering the watersheds responded with the highest proportion of rainfall becoming runoff when peak 5-min intensities were highest (Table 4.3). Comparisons were made plotting rainfall amount against peak 5-min rainfall intensities for each rainfall event when overland flow from the hillslopes occurred (Figure 4.3). Rainfall events were divided using the corresponding groups of runoff coefficients; less than 0.04 and 0.05 or greater. Rainfall events with the highest 5-min peak intensities were clearly identified but there was considerable variability of runoff coefficients at intensities below 24 mm/h.

Peak 5-min intensities did not completely describe the characteristics of the rainfall event. For rainfall events that either began with a high 5-min peak intensity and then stopped or continued at a very low intensity after the initial high intensity, runoff coefficients were low. Therefore rainfall amounts were compared to the corresponding highest 30-min intensity during individual rainfall events to improve the separation of runoff coefficients so a threshold could be defined (Figure 4.4). This relationship improved the separation of rainfall events with the higher and lower runoff coefficients within the plot, but there was still a cluster at peak 30-min intensities of lower than 10 mm h^{-1}. Rainfall amounts plotted against the corresponding product of peak 5-min and peak 30-min intensity further improved the separation of runoff coefficients such that some general thresholds could be defined (Figure 4.5).

Runoff coefficients for the hillslope frames within the Sandy Subsoil Watershed of < 0.05 occurred when rainfall amounts were below 25 mm and the product of the 10-min and 30-min intensities (both mm h^{-1}) was less than 100 (Figure 4.5). For the West Watershed, runoff coefficients < 0.05 occurred when total rainfall amounts were less than 30 mm and the product of 10 min and 30 min intensities (both mm h^{-1}) was less than 500 (Figure 4.6).

Microframe runoff coefficients were similar for the rainfall events of June 21-23 and July 21, 1993 (Table 4.1), but there was no watershed flow for June 21-23 due to differences in storm characteristics. The instantaneous peak intensity was higher for the June storm than the July storm, but the peak occurred at the start of the rainfall event (Figure 4.7). Rainfall intensity was low and intermittent after the initial peak. The overland flow from the hillslopes filled depressional areas and infiltrated before it reached the catchment outlet. In contrast, instantaneous peak intensity during the July storm occurred 8 hours after the commencement of the rainfall event (Figure 4.8). Depressional areas in the catchment channel would have begun to fill, storage on the hillslopes would be reduced by rain prior to peak intensity and the infiltration rate along the channel would have been reduced by this time.

4.3.4. Snowmelt

Runoff coefficients were higher for the hillslope frames than for the watersheds during snowmelt events. Hillslope flow often occurred during mid-winter melts or melts subsequent to the major snowmelt, but watershed flow during these events was less likely.

There were five snowmelt events during winter 1992-1993: early December 1992, late January 1993 and three separate snowfall and snowmelt periods in February and March 1993. The first snowmelt monitored began February 27 and finished March 7, a second melt occurred between March 20 and 23 and a third on March 29 to 30.

During winter 1993-1994, there was a late December melt when the watersheds cleared of snow and depression storage filled. The principal melt (defined as the period of sustained melt in the spring when the majority of snowmelt occurs) extended from March 11 to 31 and was interrupted only from March 19 to 23. There was no additional snowfall once melt commenced. A fairly shallow snowpack in 1995, similar to 1993, resulted in 2 early melt periods (January 30 to February 9 and February 21 to 24) prior to the principal melt of March 11 to 18.

The average runoff coefficient for the frames for the 1993 principal melt from the Sandy Subsoil Watershed was 0.42 (Table 4.4). The watershed runoff coefficient could not be calculated due to an insufficient drainage channel that caused backwater problems in the Watershed. The runoff coefficient averaged from hillslope overland flow for the second March melt was 0.32, but there was no watershed discharge.

For the West Watershed, runoff coefficients for both 1993 snowmelt periods calculated from the hillslope microframes (0.79, 0.67) were more than double the watershed runoff coefficients (0.30, 0.14).

Runoff coefficients during the principal melt of 1994 were numerically higher for the Sandy Subsoil Watershed than for the West Watershed (Table 4.4). There was a fairly even snowpack on both the north and south aspects prior to the melt and unlike 1993, there was an even, sustained melt period. Frame runoff coefficients were substantially higher than watershed runoff coefficients in both watersheds although the frame runoff coefficients reported may be higher than actual due to the ice-jamming problem encountered with the hillslope frames during this melt (as mentioned in Chapter 3), particulary in the Sandy Subsoil Watershed.

A fairly shallow snowpack in 1995 once again resulted in a dynamic snowpack and snowmelt runoff during midwinter warm spells. Microframe runoff coefficients for the two February melts were similar between watersheds. Measureable flow from both watersheds only commenced during the March 11 to 18 melt period. Runoff coefficients for the hillslope frames were higher than the watershed runoff coefficients, consistent with previous years.

4.4. DISCUSSION

4.4.1.Summer

Runoff coefficients obtained from the hillslope microframes of both watersheds can not be used to predict how the watersheds respond with flow to summer rainfall events. From the hillslope frames, one would justifiably conclude that there would be a substantial amount of runoff from the Sandy Subsoil Watershed during summer rainfall events and not as much from the West Watershed. But as described, these two reclaimed watersheds respond not as hypothesized nor similarly due to different channel processes happening within them. The problems of extrapolating results from hillslope frames or small plots to predict catchment or basin flow described in other studies (de Boer and Campbell, 1989; Blösh and Sivapalan, 1995) are certainly evident within these two reclaimed watersheds.

The magnitude and frequency of hillslope overland flow that occurred within the Sandy Subsoil Watershed were not matched within the West Watershed, but watershed runoff from the West Watershed occurred during rainfall events in 1993 and 1995 with return periods of as little as 2 years (Figure 4.9). The clay to clay loam subsoil within this watershed had better water-holding capacities than did the sandy loam subsoil within the Sandy Subsoil Watershed, and standing water often remained in the depressions along the channel of the West Watershed for several days after a rainfall event. Higher antecedent soil moisture, in combination with a steeper channel gradient and a main channel depression that was closer to the outlet, also likely contributed to the higher summer runoff frequency from the West Watershed. Flow from the West Watershed occurred even though few hillslope frames yielded any overland flow. Rain falling directly on the saturated channel, or a saturated area within the watershed, was the source of the surface flow from these events, rather than the hillslopes.

Rodriquez-Iturbe (1986) described basin runoff as the interaction of two related subsystems (hillslope and channel); the hillslopes produce the runoff and the channel network transports water to the outlet. The hillslopes within the Sandy Subsoil Watershed generated substantial overland flow from most summer storm events, but the channel was effective in retaining the hillslope flow. Channel transmission losses occur within many diverse basins when the permanent water table lies below the level of the channel (Pilgrim et al., 1982). Shpak (1969) attributed the apparent discrepancy of less runoff with increasing contributing area within forest-free watersheds in Russia to channel transmission losses that increased with increasing channel length.

Channel transmission losses due to infiltration or retention storage removed most of the hillslope overland flow that could potentially be watershed runoff within the Sandy Subsoil Watershed. Channel transmission losses also occur within the West Watershed as evidenced by the higher runoff coefficients from the hillslopes than for the watershed, but unlike the findings of Shpak (1969), channel losses were higher in the watershed with the shortest channel length (Sandy Subsoil).

Monthly rainfall amounts are less important in determining flow from the two reclaimed watersheds than are the characteristics of the individual rainfall events. Total rainfall amounts in June and July 1993, June 1994 and July and August 1995 were above 100 mm but runoff from the Sandy Subsoil Watershed occurred only twice when the summer storms had the highest return periods (greater than 1:10 yr). Overland flow from the hillslope microframes occurred frequently during the less intense summer rainfall events within this watershed, but often a few frames yielded the bulk of the surface flow. Watershed flow from the Sandy Subsoil Watershed occurred when all the frames contributed overland flow in near equal amounts. The hillslopes of the West Watershed were not as effective at generating runoff as those of the Sandy Subsoil Watershed. The July 21, 1993 rainfall was the only event where all twelve hillslope frames located within the West Watershed contributed overland flow. Lower surface bulk density and lower hillslope gradient contribute to the better hillslope infiltration within this watershed.

The relationship of rainfall amount to the product of 5-min and 30-min intensities for identification of thresholds for determining whether substantial hillslope runoff occurs is clearer for the West Watershed than for the Sandy Subsoil Watershed. An August 24, 1993 rainfall event resulted in a runoff coefficient of 0.39 even though the rainfall amount and the product of 5-min and 30-min intensities were below the thresholds identified for a runoff coefficient of less than 0.05.

Generally, runoff coefficients were higher in August than in June or July for similar rainfall events. For example, on June 8, 1994 the rainfall amount was 21 mm, the product of 5-min and 30-min rainfall intensities was 72 mm^2 h^{-2} and the runoff coefficient was 0.01 (Table 4.2). An event with similar characteristics occurred on August 7, 1993 and the runoff coefficient was 0.19 (Table 4.1). Factors such as antecedent soil moisture, antecedent rainfall and vegetation density and height alter rainfall/runoff relationships.

4.4.2. Snowmelt

Predicting watershed runoff from hillslope microframes within these two reclaimed watersheds during snowmelt periods would substantially overestimate runoff volume and therefore the runoff coefficient. Runoff coefficients from the hillslope frames within the West Watershed were greater than twice the actual watershed runoff coefficients and 1.4 to 1.6 times higher within the Sandy Subsoil Watershed. The higher runoff coefficients for the hillslope microframes are not consistent with the findings of Kane et al. (1991). They reported higher runoff coefficients from basin discharge than from the runoff plots, but unlike the Alaskan watershed in their study, the reclaimed watersheds in this study did not have evidence of water tracks or preferential flow paths to the channel.

The timing of snowmelt watershed runoff corresponded closely with the occurrence of runoff from the hillslope microframes during the principal melt, but hillslope runoff from midwinter melt periods and subsequent snow accumulations and melts, after the principal melt, did not necessarily translate into watershed runoff. There can be a substantial amount of hillslope snowmelt overland flow during mid-winter melt periods but yet no watershed discharge. Early hillslope flow fills channel depressions, infiltrates along the channel or may infiltrate within areas of enhanced infiltration further down the slope. Similarly, watershed runoff may not occur if there are subsequent snow accumulations and melts after the main melt, as in late March 1993.

4.5. CONCLUSIONS

Watershed runoff coefficients determined from overland flow measured at hillslope microplot scale overestimate the quantity of surface flow from these two reclaimed watersheds for both summer rainfall and spring snowmelt events. Transference of scale from the hillslope plot scale to the watershed scale is incomplete without an understanding of the processes occurring along the channel areas within the individual watersheds.

Even during major summer rainfall events, runoff coefficients for the two reclaimed watersheds were generally less than they were during snowmelt. Watershed runoff from the Sandy Subsoil Watershed during summer occurred only during rainfall events that had return periods of greater than 10 years, while it occurred from the West Watershed for events that had return periods of as little as 2 years.

The combination of rainfall amount and the product of 5-min and 30-min intensities gave a sense of the magnitude of the runoff coefficients for the hillslopes within both watersheds. Runoff coefficients for the hillslopes within the Sandy Subsoil were generally above 0.05 when the rainfall amount is above 25 mm and the product of 5-min and 30-min intensity was above 100. Similarly, runoff coefficients for the hillslopes of the West Watershed were above 0.05 when the rainfall amount is above 35 mm and the product of 5-min and 30-min intensity is above 500.

Substantial hillslope runoff may occur during midwinter melts or subsequent snow accumulations and melts after the main melt but watershed runoff is less likely during these events.

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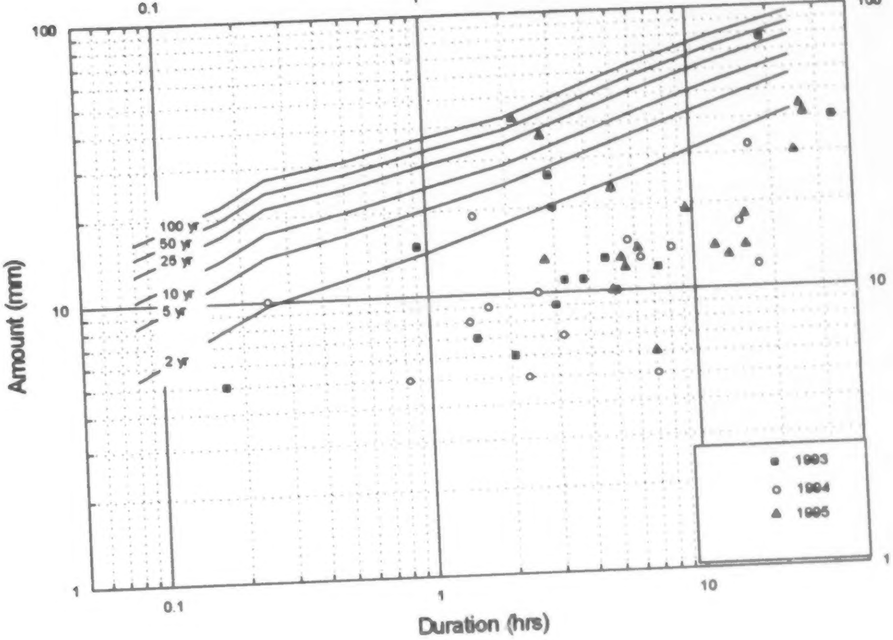

Figure 4.1. Amount-frequency-duration curves for summer rainfall events for 1993-1995 (Records from Edmonton International Airport used to compile the long-term curves)

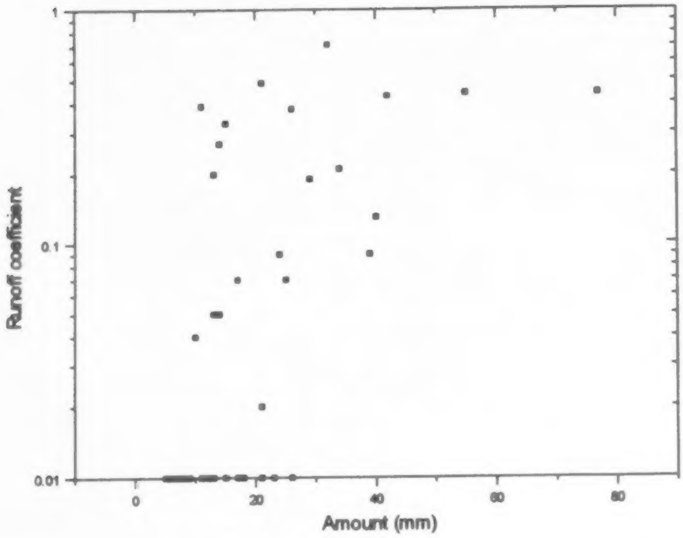

Figure 4.2. Relationship between runoff coefficient and rainfall amount for the hillslopes on the Sandy Subsoil Watershed.

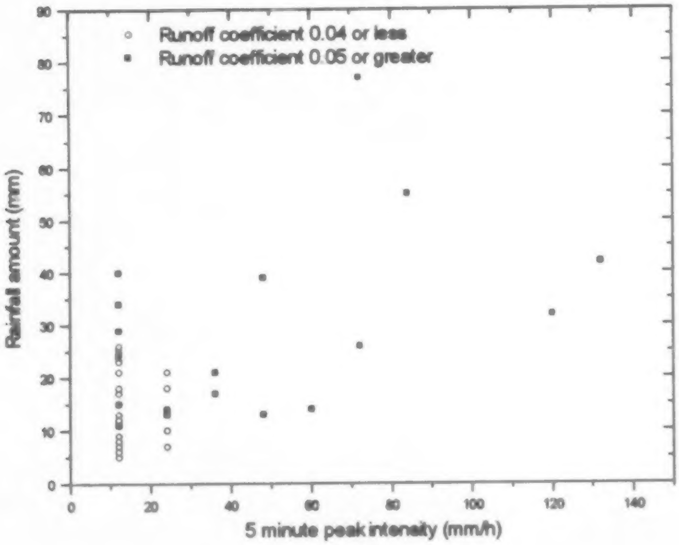

Figure 4.3. Separation of runoff coefficients based on rainfall amount and peak 5-min intensity.

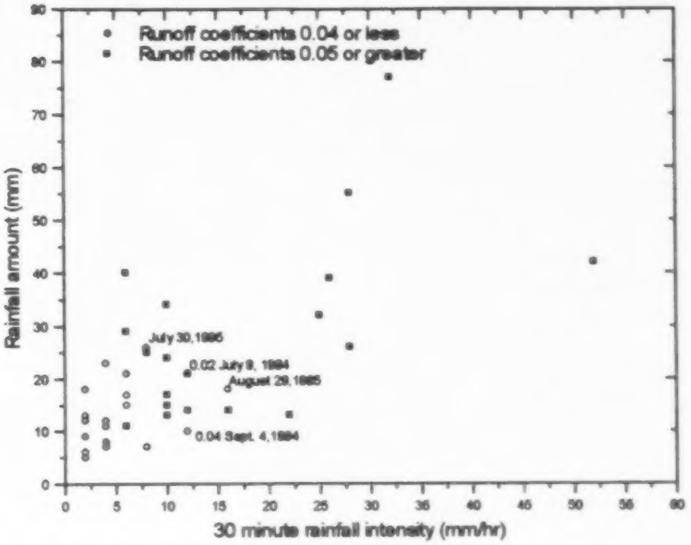

Figure 4.4. Separation of runoff coefficients based on rainfall amount and peak 30-min intensity.

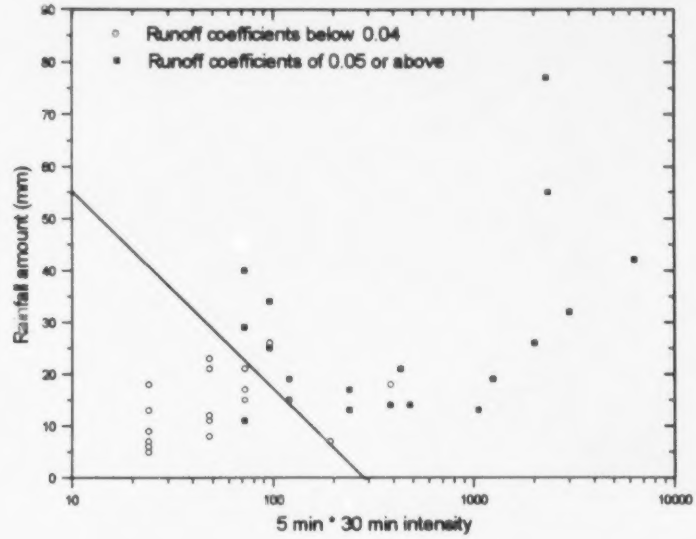

Figure 4.5. Runoff coefficients for rainfall amount compared to product of peak 5-min and peak 30-min intensity for the Sandy Subsoil Watershed.

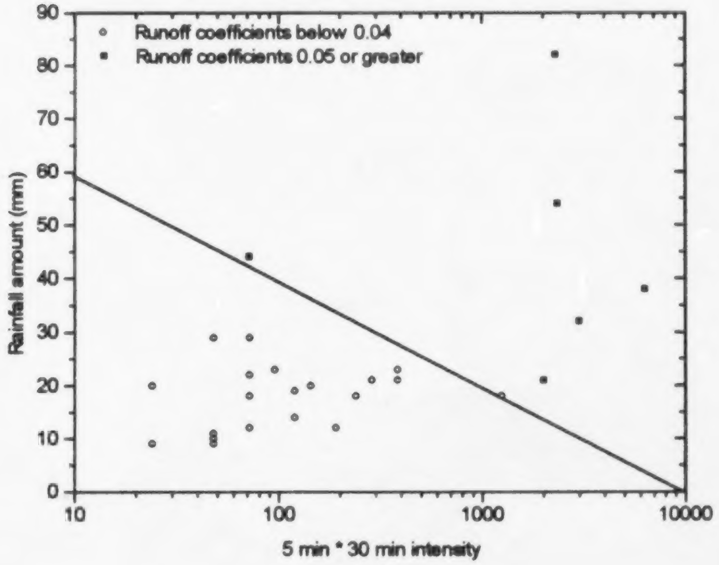

Figure 4.6. Runoff coefficients for rainfall amount compared to product of peak 5-min and peak 30-min intensity for the West Watershed.

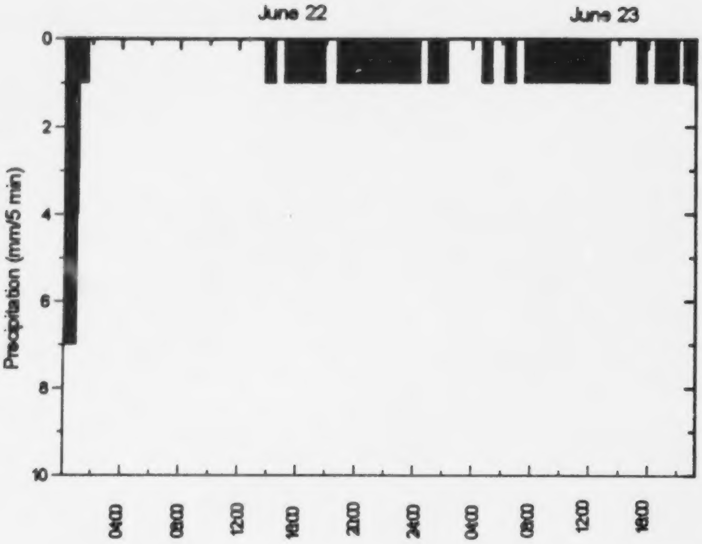

Figure 4.7. Hyetograph for the rainfall of June 21-23, 1993 (no watershed flow).

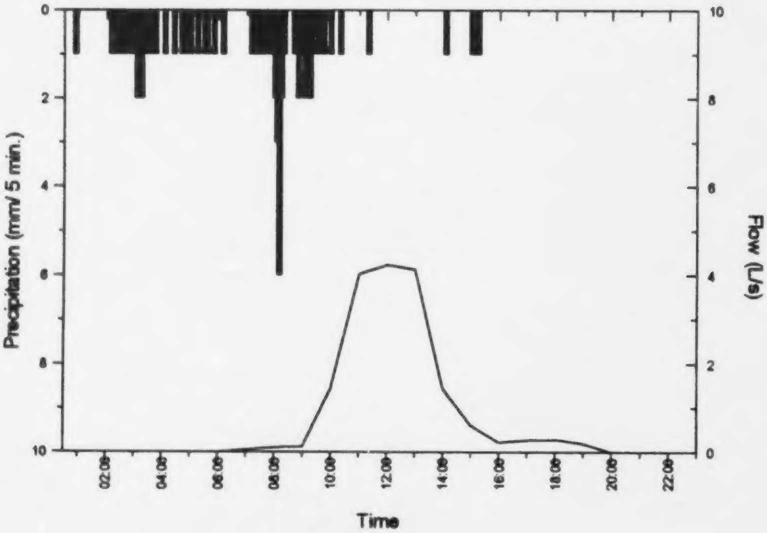

Figure 4.8. Hyetograph and discharge from the Sandy Subsoil Watershed on July 21, 1993.

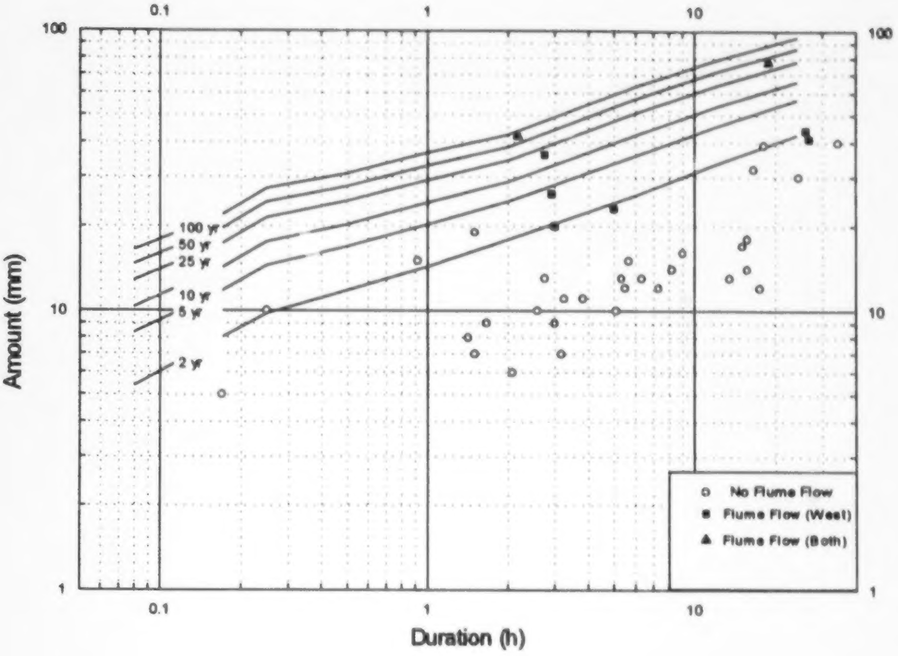

Figure 4.9. Characteristics of summer rainfall events that resulted in either frame runoff or watershed flow or both for 1993-1995.

Note: Hillslope runoff from at least one frame occurred for all events shown.

Table 4.1. Runoff coefficients for catchment and extrapolated microframe runoff for summer 1993.

	Sandy Subsoil Watershed						West Watershed			
		Peak intensity (mm/h)		Runoff Coefficient				Runoff Coefficient		
Date:	Precip. Amount (mm)	5 min	30 min	Watershed	Frame	No.of frames contrib.	Precip. Amount (mm)	Watershed	Frame	No.of frames contrib
7-May	17	12	6		<0.01	3	18		<0.01	1
26-May	25	12	8		0.07	8	29			
12-Jun	5	12	2		<0.01	3	5			
21-Jun to 23-Jun	55	84	28		0.44	12	54		0.08	5
27-Jun a.m.	13	24	10		0.05	8	18		<0.01	2
27-Jun p.m.	26	72	28		0.38	12	21	0.003	0.10	3
21-Jul	77	72	32	0.023	0.44	12	82	0.029	0.29	12
28-Jul	7	24	6				20	0.006	<0.01	1
7-Aug	29	12	6		0.19	11	29		<0.01	7
24-Aug	11	12	6		0.39	12	12		<0.01	4

Table 4.2. Runoff coefficients for catchment and extrapolated microframe runoff for summer 1994.

	Sandy Subsoil Watershed					West Watershed		
		Peak intensity (mm/hr)						
Date	Precip. Amount (mm)	5 min	30 min	Runoff Coefficient Frame	No. of frames contrib.	Precip. Amount (mm)	Runoff Coefficient Frame	No. of frames contrib.
16-May	23	12	4	0.01	11	29	<0.01	9
20-May	11	12	4	<0.01	6	11	<0.01	6
2-Jun	9	12	2	<0.01	8	9	<0.01	6
8-Jun	21	12	6	<0.01	7	22	<0.01	3
12-Jun	39	48	26	0.35	7	32	0.03	5
26-Jun	7	24	8	0.01	4	12	<0.01	1
29-Jun	17	24	10	0.08	3	19		
2-Jul	8	12	4	<0.01	2	9	<0.01	1
3-Jul	24	12	10	0.11	8	26	<0.01	6
9-Jul	21	24	12	0.02	9	21	<0.01	8
18-Jul	8	12	4	<0.01	6	9		
7-Aug	14	24	16	0.27	9	21	<0.01	8
9-Aug	15	12	10	0.34	9	14	<0.01	7
17-Aug	34	12	8	0.21	12	23	<0.01	3
4-Sep	10	12	12	0.04	12	15	<0.01	4
9-Oct	23	n/a	n/a	0.27	12	22	0.01	5

* There was no flow from either watershed during any rainfall event during summer 1994.

Table 4.3. Runoff coefficients for catchment and extrapolated microframe runoff for summer 1995.

	Sandy Subsoil Watershed						West Watershed			
		Peak intensity (mm/hr)		Runoff Coefficient				Runoff Coefficient		
Date:	Precip. Amount (mm)	5 min	30 min	Watershed	Frame	No.of frames contrib.	Precip. Amount (mm)	Watershed	Frame	No.of frames contrib.
25-Apr	7	12	2		<0.01	4	7			
15-May	15	12	6		<0.01	5	14			
3-Jun	12	12	4		<0.01	8	10		<0.01	1
16-Jun	6	12	2		<0.01	1	7			
18-Jun	21	36	12		0.49	12	18			
24-Jun	13	48	22		0.20	10	13			
4-Jul	13	12	2		<0.01	8	13			
23-Jul	14	48	10		0.05	12	12			
25-Jul	32	120	25		0.71	12	36	0.04	0.22	10
30-Jul	26	12	8		<0.01	10	30			
5-Aug	18	12	2		<0.01	11	20		<0.01	2
9-Aug	40	12	6		0.13	7	44	0.07	0.31	5
11-Aug	12	12	4		<0.01	4	14	0.14[a]		
16-Aug	42	132	48	0.19	0.43	12	38	0.26	0.43	6
29-Aug	18	24	16		<0.01	3	23	0.01	<0.01	1

[a] flow was still occurring from the August 9 rainfall event when the August 11 rainfall event occurred.

Table 4.4. Microframe vs watershed runoff coefficients for 1993, 1994 and 1995 snowmelt.

	West Watershed			Sandy Subsoil Watershed		
Melt Period	Snow Water Equivalents (mm)	Frame	Watershed	Snow Water Equivalents (mm)	Frame	Watershed
Feb 27-Mar 7 1993	59	0.79	0.30	51	0.42	n/a[c]
Mar 20 - Mar 23 1993	16[a,b]	0.67	0.14	12[a,b]	0.32	0.00
Mar 11 - Mar 31 1994	119[a]	0.61	0.28	88[a]	0.76	0.46
Feb 1- Feb 9 1995	13[a,b]	0.18	0.0	28[a]	0.22	0.0
Feb 21- Feb 24 1995	11[d]	0.33	0.0	19[d]	0.33	0.0
Mar 11-Mar 18 1995	9[d]	0.57	0.23	15[d]	0.39	0.28

a - average of 10 replicates

b - bare sections on south-facing slopes

c - backwater problems with Watershed prevented runoff coefficient determination

d - ice layer on north-facing slope from previous melt period

5. SPATIAL AND TEMPORAL VARIATION OF SNOWMELT RUNOFF AND SOIL MOISTURE RECHARGE FROM TWO RECLAIMED SURFACE MINED WATERSHEDS

5.1. INTRODUCTION

The process of snowpack melting is fairly well described (Granger and Gray, 1990), and is primarily determined by energy exchanges at the air/snow and snow/soil interface, and by the physical characteristics of the snowpack (Kane et al., 1991; Dingman, 1994).

The snowmelt process does not occur uniformly within a watershed; often there are major differences in the timing and amount of overland flow from hillslope plots with similar snow accumulation and snow density characteristics (Lewkowicz and French, 1982; Kane et al., 1991). The type and extent of soil frost influences the amount of infiltration and hence overland flow (Granger et al., 1984), as does the type and extent of vegetative cover (Chanasyk and Woytowich, 1985). Soil moisture differences of the top 30-40 cm of the soil profile (defined as the active zone) prior to snowmelt are identified as the main reason that different infiltration rates and amounts, and hence variations in microscale overland flow, occur during snowmelt (Granger et al., 1984; Buttle, 1989; Kane and Chacho, 1990; Burn, 1991; Johnsson and Lundin, 1991).

Unsaturated frozen soils have lower hydraulic conductivities than unfrozen soils at the same moisture content due to ice in the larger pores of the soil (Kane and Chacho, 1990; Johnson and Lundin, 1991). Infiltration of snow melt into frozen soils can be initially high due to soil macropores or over-winter soil moisture deficits (Johnson and Lundin, 1991), but infiltration into the frozen active layer quickly declines to a rate governed by the amount and continuity of unfrozen water present in small soil pores or unfrozen water existing as a film adhering to soil particles (Burn, 1991). Although the infiltration rate of frozen soils is reduced compared to that of unfrozen soils, infiltration of up to 70% of total snow-water equivalent has been reported (Burn, 1991).

Total infiltrated volume during snowmelt based on pre-melt soil moisture and snow-water equivalent for semi-arid regions in central Saskatchewan can be estimated from an equation presented by Gray et al. (1986) as:

$$INF = a(SWE / \theta p)^n$$

where:

INF = infiltration (mm),
SWE = snow-water equivalent (mm),
θp = degree of pore saturation (cm^3/cm^3) and
a, n = empirical derived coefficients.

Hayhoe et al. (1993) tested a form of this equation for snowmelt in the Peace River region of Alberta. There was reasonable agreement with the coefficients used by Granger et al. (1984) for varying soil moisture contents.

A description of the spatial and temporal variability of snowmelt within a watershed requires better definition for input into distributed parameter, energy-balance snowmelt models (Leavesley, 1989; Bloschl et al., 1991). Equally, the variability of factors influencing the amount and timing of snowmelt runoff from within a watershed has to be described since watershed runoff response from snowmelt reflects the contributions from the different hillslopes, aspects and land uses within the watershed.

Field research reported here was conducted over three annual snowmelt periods to examine the spatial and temporal variability of hillslope overland flow during snowmelt runoff from two reclaimed surface mined watersheds. The hypothesis was that snowmelt runoff (timing and volume) occurs uniformly within two reclaimed watersheds.

5.2. LOCATION

Refer to Chapter 3 for a description of the study area and for description of watersheds.

5.3. METHODS AND MATERIALS

The hypothesis was tested by relating differences in snowmelt runoff to aspect, pre-winter soil moisture and/or snowmelt infiltration.

See Chapter 3 for general description (in addition).

5.3.1. Soil Moisture and Temperature

Over-winter soil moisture gain or loss was defined as the difference between the last soil moisture readings in fall of the previous year and the first soil moisture readings in spring after snowmelt. The fall soil moisture readings were taken on November 16, 1992 and October 13, 1993. Spring soil moisture readings were taken on April 15, 1993 and May 4, 1994. The snow-cover period of 1994-1995 was excluded for over-winter infiltration analysis since the final soil moisture readings for 1994 were taken in the middle of September, perhaps too early to be truly representative of fall soil moisture conditions.

Hillslope soil temperatures during the melt were taken to relate the influence of soil temperature on snowmelt infiltration. The nearer soil temperatures are to 0 °C, the more snow melt should infiltrate. Soil temperatures were obtained from nests of thermistors (5, 10, 20 and 40 cm depths) installed adjacent to each hillslope frame on the Sandy Subsoil Watershed, and from a single nest between the three frames on similar slope steepness and aspect within the West Watershed. Soil temperature readings were taken between 1300 and 1500 h throughout the melt period in 1993 and less frequent during the 1994 melt.

Statistical significance was determined for soil temperature and overland flow using the Least-Significance Difference ($p \leq 0.05$) procedure for a non-randomized block design outlined in the SAS Users Manual (1987).

5.4. RESULTS

5.4.1. Meteorology

See Chapter 3

5.4.2. Timing and Volume of Snowmelt

Hillslope snow melt runoff did not occur uniformly throughout the two reclaimed watersheds. South-facing aspects of both watersheds commenced runoff the earliest, cleared of snow the soonest into the melt and yielded the least amount of snowmelt runoff.

Within the Sandy Subsoil Watershed for all years, the frames located on the south-facing aspect contributed the most runoff during the first day of melt, but by the second or third day of melt, the frames located on the north-facing aspect were contributing the most runoff. Within the West Watershed the frames on the south-facing 13% slope contributed the most runoff during the first day, and those on the south-facing aspect contributed most during the first two days of the melt. The differences in timing and volume of hillslope runoff during the main snowmelt within the Sandy Subsoil and West Watersheds was similar for 1994 and 1995 as it was in 1993 (Tables 5.1-5.6).

In contrast to the main snow melt, there was more runoff from north-facing aspects of both watersheds during December melts in both 1993 and 1994. Similarly, there was no overland flow from the south-facing frames in the Sandy Subsoil Watershed during a second melt on March 20, 1993 even though snowfall accumulations of 12 cm occurred during the period from March 9 to 19.

There was high variability of flow from different aspects and slope positions as evidenced by high coefficients of variation in Tables 5.1-5.6. Occasionally snowmelt runoff volumes for replicated frames differed by an order of magnitude. Snowmelt runoff from frame SNU3 within the Sandy Subsoil Watershed was minimal during all years of monitoring with no snowmelt runoff during melt 1995. Similarly, snowmelt runoff from frame WNF3 located within the West Watershed was minimal during all years of monitoring.

5.4.3. Soil Temperature

Within the Sandy Subsoil Watershed, soil temperatures were significantly higher for the south-facing slope compared to the north-facing slopes at the 10-cm and 20-cm depths throughout most of the 1992-1993 snow-cover period (Table 5.7). Soil temperatures at the 5-cm depth were more variable but significantly higher for the south-facing aspect at the commencement of the melt on February 27, 1993. The lowest soil temperatures at all depths were generally for the frames on the north-facing lower slope position. Soil temperatures were similar for all depth intervals and both aspects prior to the commencement of the melt on March 12, 1994. The deep snow-cover insulated the ground and buffered the soil from the influence of energy inputs to the snowpack.

The influence of aspect on soil temperatures within the West Watershed was similar to that within the Sandy Subsoil Watershed during the 1992-1993 snowcover period. Soil temperatures were higher at all depths for the south-facing than for the north-facing aspect during the early part of the melt. Soil temperatures were similar at all depths during the second melt in late March 1993.

Soil temperatures at a 5-cm depth did not rise above 0 °C for either the south- or north-facing aspects of either watershed during the entire main melt period of 1993. At the end of the melt in 1994 (March 26) soil temperatures were still below 0 °C to a depth of 40 cm. Interestingly, the highest soil temperature recorded during the melt period was at the 40-cm depth for the north-facing aspect of the West Watershed on March 9, 1993 (Table 5.4; +0.4°C).

5.4.4. Pre-winter Soil Moisture and Meltwater Infiltration

Fall soil moisture was generally higher for the north-facing aspect than for the south-facing aspect on November 16, 1992 (Figure 5.1). The highest pre-winter volumetric moisture content to a depth of 40 cm occurred at the SNU1 slope position (Figure 5.1) and the SSL2 slope position (Figure 5.1). The largest over-winter soil moisture loss also occurred at these slope positions (Figure 5.2). Similarly, in frames SNU2, SNU3 and SSL3, fall soil moisture was lowest and overwinter soil moisture gain was greatest for their respective slope positions. The two frames on the south-facing aspect at the upper slope position which yielded the least amount of runoff during this snowmelt period were SNU1 and SNU3 (Table 5.1), with the highest and lowest pre-winter soil moistures.

Soil moisture gain/loss was remarkably similar for the frames located on the north-facing aspect at the upper slope position within the Sandy Subsoil Watershed, even though runoff was quite different for the three frames (Table 5.1). No problems were encountered for the frames at this slope aspect and position during the melt period so differences in runoff could possibly be due to increased evaporation from the SSU1 microframe. This frame was located at the most upper slope position of the three SSU frames and was exposed to incoming solar radiation for longer periods during the day.

Soil moisture increases were recorded to at least 85 cm at 4 slope positions within the Sandy Subsoil Watershed in 1993, but the soil zone with the greatest gain in soil moisture appeared to be above 40 cm; consistent with the active layer definition of 30 cm presented by Granger et al. (1984).

The influence of fall soil moisture on snowmelt infiltration is quite clear for the frames located on the WNF slope position within the West Watershed. In the frame with the lowest fall soil moisture (WNF2, Figure 5.3) soil moisture gain during snowmelt was the highest (Figure 5.4), while a net soil moisture loss over winter occurred in the frame with the highest fall soil moisture (WNF1). Fall soil moisture was similar for the frames at the other slope positions within the West Watershed, therefore, differences in snow-water infiltration would be a function of different soil surface or snowpack conditions during snowmelt. For example, the greatest volume of snowmelt runoff from the frames located on the WSS slope position was from frame WSS2 (Table 5.2), yet the highest soil moisture gain during snowmelt also occurred in this frame.

Soil moisture on October 13, 1993 was slightly lower for frames on the south-facing aspect of the Sandy Subsoil Watershed than in 1992 (Figure 5.5), and similar between years for the frames on the north-facing aspect. Soil moisture in the upper 70 cm of the profile was substantially higher in frame SNU1 than the other two frames at this slope position. Consistent with some trends in 1993, soil moisture gain during snowmelt was also lowest for this frame (Figure 5.6).

Melt-water infiltrated to at least the depth of monitoring in eight of the twelve microframes located in the Sandy Subsoil Watershed during winter 1993-1994. The greatest gain of soil moisture for all frames occurred in the active layer. The snow accumulation and ablation periods for 1993-1994 were not as dynamic as those for 1992-1993. Only one major mid-winter melt occurred near the end of December, 1993 and once the melt progressed in the middle of March, 1994 there were no additional accumulations of snow. Mid-winter melts can lead to saturated surface conditions that, upon freezing, impede infiltration during subsequent snowmelt events (Price and Hendrie, 1985).

Soil moisture profiles within the West Watershed in fall 1993 (Figure 5.7) were almost identical to those of 1992 (Figure 5.3), but there was greater infiltration during snowmelt in 1994 (Figure 5.8) than in 1993 (Figure 5.4). This lends support to the relationship developed by Granger et al. (1984) wherein infiltrated volume of meltwater increases as snow-water equivalent increased (see Table 3.4, Chapter 3 for snow-water equivalents). Patterns of over-winter soil moisture gain that remained consistent between both years were seen in frames WSS2 and WSF2. In both of these frames infiltrated volume and depth of infiltration were highest for the frames at similar slope positions. In some frames consistently characterized by net soil moisture losses in 1993 and 1994, pre-winter soil moisture at their respective slope positions were higher (for example WSF3 and WNF1); but in WSS1, a soil moisture loss occurred during snowmelt in both years and pre-winter soil moisture was not high.

5.4.5. Pre-winter Soil Moisture and Proportion Runoff

There was no discernible trend or pattern between the snow melt runoff coefficients for frames and the pre-winter volumetric soil moisture content averaged for the upper 45 cm of the soil profile (Figure 5.9), nor between snow-water equivalent and infiltration (Figure 5.10). Mid-winter melt during all three years of monitoring likely masked the influence of fall soil moisture in the active zone (0-40 cm) on snowmelt runoff. Meltwater during mid-winter melts would have increased soil moisture prior to the main melt each year.

From snowmelt mass balance calculations for select microframes from both watersheds, evaporation and/or sublimation from the snowpack for the overwinter periods 1993 and 1994 varied between 0.05 and 0.74 of the snow-water equivalent (Table 5.9). Higher evaporation proportions were calculated for the south-facing aspect (0.47) than for the north-facing aspect (0.38) within the Sandy Subsoil Watershed and for the south-facing aspect (0.43) than for the north-facing aspect (0.28) within the West Watershed.

Snowmelt infiltration along the hillslopes is negligible when the runoff coefficient is greater than 0.65 (Figure 5.11). Evaporation and sublimation should account for the balance of the snow-water available at the start of the melt.

5.5. DISCUSSION

5.5.1. Influence of Aspect

Incoming solar radiation is the dominant parameter in the energy balance equation for more northerly areas (Braun and Slaymaker, 1981; Hinzman et al., 1991), governing the timing of melt and the snowmelt rate (Granger and Gray, 1990). Albedo reduces the net energy available for melt and is a function of snow grain size, solar zenith angle, and surface deposition of particulates (Marshall and Warren, 1987). Albedo varies with aspect (Blöschl et al., 1991); with the lower albedo reported for the south-facing aspects. Olyphant (1986) showed how longwave emission from adjacent snowfree areas within mountainous terrain can contribute melt energy to the snowpack. Similar advective energy transfer was identified as a secondary energy source for ablation within a forested area in Alberta (Berry and Rothwell, 1992). Within the reclaimed watersheds, the south-facing slopes were more directly exposed to daily incoming solar radiation than were the north-facing slopes. More energy available for snowmelt from incoming solar radiation and advection of sensible heat from nearby snow-free areas once the melt has progressed would translate to an earlier appearance of meltwater and a shorter melt period for the hillslopes with the south-facing aspect.

The parameters that influence the differences in volume of snowmelt runoff between aspects can be combinations of differences in: snow-water equivalents, infiltration and evaporative losses. Snow-water equivalents prior to the principal melt in both 1993 and 1994 were slightly higher for the south-facing than the north-facing aspect of the Sandy Subsoil Watershed (see Chapter 3, Table 3.4). Therefore, the lower snowmelt runoff volume from the south-facing aspect must be related to differences in infiltration and/or evaporation and not differences in snow depths (see Figure 5.11).

At soil temperatures slightly below 0 °C, a considerable portion of the soil moisture can exist in the unfrozen state (Burn, 1991) facilitating melt-water infiltration. Soil temperatures on south-facing aspects were higher than those on north-facing aspects during the snowmelt period and greater infiltration was generally observed.

Bengtsson (1980) proposed that evaporation from a snowpack is a minor component of the mass balance equation during snowmelt, usually averaging less than 1 mm per day or 10 to 20 mm for the snow ablation period. Near saturated conditions of the air immediately above the snow surface minimizes the vapor pressure gradient necessary for evaporation to proceed. However, total evaporation during snowmelt from an Arctic watershed varied between 20 to 34% of the snow-water equivalent and between 10 to 65% from runoff plots located on a south-facing hillslope (Kane et al., 1991). From mass balances to apportion melt-water, average evaporative losses within the two reclaimed watersheds were within the range or higher than reported by Kane et al., 1991. Evaporative losses were higher for the south-facing rather than for the north-facing aspects for both watersheds during the melts.

Since average fall soil moisture of the Sandy Subsoil Watershed was consistently lower to depths of 95 cm for the south-facing aspect than for the north-facing aspect, there would be more opportunity for the first meltwater to fill the unsaturated pore space once snowmelt water appeared at the bottom of the snowpack, translating to less water available for runoff. This could in part explain why the south-facing aspects did not produce any runoff during some mid-winter melt periods.

5.5.2. Infiltration and Redistribution of Melt-water

Reduced infiltration occurs when soil moisture is high prior to the melt period (Kane et al., 1991) or there is a restriction to infiltration (Granger et al., 1984). Consequently more of the snow-water becomes runoff and runoff coefficients are subsequently high. When the runoff coefficients for the microframes were higher than 0.65, minimal or no snow-water infiltration occurred over-winter.

The relationship identified by other researchers for pre-winter soil moisture in the upper 40 cm of the soil and the amount of infiltration and hence runoff from the hillslope frames was not evident for these reclaimed fields. Soil moisture increases during the mid-winter melts in all three years may have masked the differences in soil moisture evident from fall soil moisture readings. Even the relationship between snow-water equivalent and infiltration shown for central Saskatchewan by Granger et al. (1984) is not evident from the snowmelt data on the reclaimed watersheds. The difficulty with applying these relationships is that there were not distinct snow accumulation and snow ablation periods during the three years of the study. During the 1992-1993 snow period, there were five separate snow accumulation-ablation periods, in 1993-1994 there were two, and in 1994-1995 there were four. A major mid-winter melt can dramatically change surface soil moisture conditions, the nature of the soil frost and snowpack conditions for subsequent snowmelt periods.

During snowcover periods 1992-1993 and 1993-1994 there was considerable microscale variability in infiltration amounts and thus depth of infiltration throughout a watershed. Differences in infiltrated amounts of greater than 40 mm occurred for replicated frames at similar slope positions and aspects within the West Watershed during the snow-cover period 1993-1994.

There appears to be evidence of soil moisture redistribution or loss at depths greater than 40 cm during the over-winter period. Burn (1991) reported overwinter soil moisture losses to the bottom of the pack of up to 4 mm from the surface layers of a soil, but this loss was replenished from soil water at greater depths. Net soil moisture decreases at depths below 30-40 cm for eight of the twelve frames within both watersheds during 1992-1993 snowmelt indicates that either upward or downward soil moisture loss or lateral soil moisture redistribution occurs during the snowcover period.

5.5.3. Quality of the Data

The input components for the mass balance equation during snowmelt are extremely difficult to quantify using hillslope frames. The diurnal thawing during the day and freezing at night created ice accumulation problems within and around the collection buckets during the 1993 melt, and resulted in leakage of meltwater from outside of the frame into the top of some collection buckets. In 1994, probably due to a deeper premelt snowpack, meltwater from upslope of some hillslope frames would accumulate behind the upslope border of the frames and freeze during the evening. Additional meltwater from upslope would overflow the rear frame border and contribute to measured flow from within the collection system.

In 1995, the problems with the hillslope frames were seemingly solved, but it was extremely difficult to accurately determine snow-water equivalents for the frames since major mid-winter melting created an uneven ice layer within and outside of the hillslope frames. Additionally there was still surface flow within the hillslope frames when there was no snow evident within the frame. A thin, near-surface saturated layer was contributing interflow runoff to the downslope collection system. If the downslope frame border was not there, interflow most likely would have continued downslope uninterrupted, but because the interflow path was interrupted by the frame border, the runoff would pool at the inlet to the collection system and contribute to measured surface flow.

5.6. CONCLUSIONS

Aspect, even for these relatively small watersheds, had a major influence on the timing and amount of runoff within the watersheds. Contributions to runoff from the watershed during the first day or two of snowmelt originated from the south-facing slopes due to the earlier appearance of meltwater.

The variability in the timing and amount of hillslope snowmelt runoff between replicated frames at similar slope positions and between slope positions along the same aspect is surprisingly high. Subtle differences in slope angle generally resulted in a difference in the timing and amount of runoff among other frames at similar aspect and slope position. Similarly, soil moisture and surface ice characteristics at certain hillslope locations delayed melt.

Differences in snowmelt runoff volumes between aspects can be related to differences in pre-winter soil moisture, energy inputs and soil temperatures. Fall soil moisture was lower, soil temperatures were higher during the melt and energy inputs should be higher (Berry and Rothwell, 1992) for the south-facing aspect than for the north-facing aspect within the Sandy Subsoil Watershed. Soil moisture differences were not evident for different aspects within the West Watershed but soil temperature was higher for the south-facing aspect and energy inputs were assumed to be higher. Distributed parameter models for predicting the timing and amount of snowmelt runoff should therefore account for the differential melt rates due to differences in aspect even within fairly small watersheds.

Soil moisture changed during the winter as a result of upward soil moisture losses, redistribution or due to mid-winter melts; such that some soil profiles had lower soil moisture post-melt than they did the preceding fall. Changes to soil moisture and soil hydraulic conductivity during mid-winter melts can render fall moisture levels unrepresentative of pre-melt levels. Hence, under these circumstances soil moisture should be measured continuously over winter to quantify the influence of mid-winter melts and the amount and direction of soil moisture redistribution.

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Table 5.1. Microframe runoff (mm) during 1992-1993 snowmelt for the Sandy Subsoil Watershed.

		13-Dec	27-Feb	1-Mar	2-Mar	20-Mar	22-Mar
SL	Mean	7.6a	0.0a	20.8a	1.7a	15.2a	0.5a
	CV	126.3	-	34.0	103.1	62.1	173.2
SU	Mean	16.4a	7.7a	10.5a	0.4a	12.7a	0.5a
	CV	72.0	121.2	89.7	150.2	88.2	39.0
NL	Mean	0.0b	7.0a	10.4a	0.1a	0.0b	0.0a
	CV		94.6	34.0	141.4		
NU	Mean	0.0b	8.5a	7.2a	0.0a	0.0b	0.0a
	CV		129.4	16.8			

* - missing coefficients of variation indicate zero runoff from slope position or data obtained from only one frame.
- means on a given date with same letter not significantly different at ($p=0.05$).

SL - south slope (north-facing) lower slope position. NL - north slope (south-facing) lower slope position.

SU - south slope (north-facing) upper slope position. NU - north slope (south-facing) upper slope position.

Table 5.2. Microframe runoff (mm) during 1992-1993 snowmelt for the West Watershed.

		13-Dec	27-Feb	28-Feb	1-Mar	2-Mar	3-Mar	4-Mar	5-Mar	6-Mar	7-Mar	20-Mar	21-Mar	22-Mar	23-Mar
SS	Mean	0.4a	0.0a	1.7a	12.4b	15.9a	6.0a	2.4a	5.1a	12.1a	4.3a	1.4a	15.7a	12.8a	0.2a
	CV	158.7		169.8	10.5	59.4	69.4	35.6	62.3	30.0	24.3	24.5	37.3	79.6	100.0
SF	Mean	0.0a	0.0a	3.3a	24.0a	8.8a	4.6a	4.1a	1.1a	1.3b	0.0b	6.7a	3.0b	0.1a	0.0a
	CV			91.7	16.1	76.1	27.2	76.2	173.2	173.2		108.2	173.2	173.2	
NS	Mean	0.0a	1.3a	5.1a	12.8b	0.7a	0.0a	0.0a	0.0a	0.0b	0.0b	3.9a	0.0b	0.1a	0.0a
	CV		141.4	1.4	2.8	141.4						0.62		1.41	
NF*	Mean	0.0	1.1	7.0	20.1	10.3	0.0	0.0	0.0	0.0	0.0	4.4	0.0	0.0	0.0
	CV														

* - missing coefficients of variation indicate zero runoff from slope position or data obtained from only one frame.

- means on a given date with same letter not significantly different at (p=0.05).

SS - south slope (north-facing) 13% slope gradient. NS - north slope (south-facing) 13% slope gradient.

SF - south slope (north-facing) 5% slope gradient. NF - north slope (south-facing) 5% slope gradient.

Table 5.3. Microframe runoff (mm) during 1993-1994 snowmelt for the Sandy Subsoil Watershed.

		26-Dec	11-Mar	12-Mar	13-Mar	14-Mar	15-Mar	16-Mar	18-Mar	25-Mar
SL	Mean	8.9a	5.9a	3.8a	19.7a	13.5a	16.0a	14.4a	2.7	3.0a
	CV	147.5		9.4	11.9	19.3	104.2	90.4		116.2
SU	Mean	15.8a	4.5a	3.3a	29.8a	23.8a	15.0	11.2a	2.0a	0.6a
	CV	39.0	13.3	31.6	29.4	26.3		36.1	49.5	173.2
NL	Mean	2.6a	12.8b	8.7a	11.4a	18.1a	17.6a	0.0b	0.0b	0.0a
	CV	40.7	10.5	81.7	141.4	139.1	86.8			
NU	Mean	2.3a	14.5b	10.4a	0.0a	14.0a	14.1a	1.1b	0.0b	0.0a
	CV	75.8	22.4	138.7		134.4	110.9	150.2		

* - missing coefficients of variation indicate zero runoff from slope position or data obtained from only one frame.

- means on a given date with same letter not significantly different at (p=0.05).

SL - south slope (north-facing) lower slope position. NL - north slope (south-facing) lower slope position.

SU - south slope (north-facing) upper slope position. NU - north slope (south-facing) upper slope position.

Table 5.4. Microframe runoff (mm) during 1993-1994 snowmelt for the West Watershed.

		26-Dec	13-Mar	14-Mar	15-Mar	16-Mar	18-Mar	25-Mar	26-Mar	27-Mar	28-Mar	30-Mar
SS	Mean	3.9a	6.3a	4.3a	3.3a	2.0a	3.0a	28.3a	39.3a	16.3a	10.1a	6.2a
	CV	95.4	34.1	5.8	18.2	10.6	7.8	60.6	23.2	91.1	125.9	153.6
SF	Mean	3.3a	6.5a	1.9a	3.3a	1.1ab	1.0a	13.1a	3.6b	29.4a	6.4a	8.7a
	CV	121.8	87.1	173.2	86.8	88.4	140.0	84.3	37.8	40.4		152.7
NS	Mean	1.0a	9.3a	0.0b	0.0a	0.1b	3.9a	0.0a	0.0b	0.0b	0.0a	0.0a
	CV	140.0	141.4			141.4	173.2					
NF	Mean	1.7a	13.6a	0.0b	3.9a	0.0b	2.2a	11.1a	5.4b	0.0b	0.0a	0.0a
	CV	173.2	45.3		173.2		141.4	136.1	151.3			

* - missing coefficients of variation indicate zero runoff from slope position or data obtained from only one frame.

- means on a given date with same letter not significantly different at (p=0.05).

SS - south slope (north-facing) 13% slope gradient. NS - north slope (south-facing) 13% slope gradient.

SF - south slope (north-facing) 5% slope gradient. NF - north slope (south-facing) 5% slope gradient.

Table 5.5. Microframe runoff (mm) during 1994-1995 snowmelt for the Sandy Subsoil Watershed.

		1-Feb	9-Feb	21-Feb	22-Feb	24-Feb	11-Mar	12-Mar	13-Mar	14-Mar	15-Mar	16-Mar
SL	Mean	0.6a	2.0a	12.2a	11.3a	2.7a	4.1a	9.1a	5.4a	9.2a	15.7a	7.9a
	CV	90.6	43.3	67.8	101.2	40.3	73.7	45.1	70.6	130.1	67.6	49.2
SU	Mean	2.7a	2.1a	8.0a	8.6a	0.8b	5.0a	9.0a	1.4b	1.6b	2.4a	0.8b
	CV	61.2	43.4	25.0	59.0	37.5	78.5	35.8	111.1	146.4	151.8	173.2
NL	Mean	16.6a	10.4b	14.1a	4.1a	0.0b	11.7b	0.6b	0.0b	0.0b	0.0a	0.0b
	CV	94.3	53.1	68.5	76.2		52.3	90.6				
NU	Mean	8.0a	5.0ab	4.0a	8.9a	0.0b	9.6b	0.2b	0.0b	0.0b	0.0a	0.0b
	CV	100.0	141.4	141.4	122.0		141.4	141.4				

* - missing coefficients of variation indicate zero runoff from slope position or data obtained from only one frame.

- means on a given date with same letter not significantly different at (p=0.05).

SL - south slope (north-facing) lower slope position. NL - north slope (south-facing) lower slope position.

SU - south slope (north-facing) upper slope position. NU - north slope (south-facing) upper slope position.

Table 5.6. Microframe runoff (mm) during 1994-1995 snowmelt for the West Watershed.

		9-Feb	21-Feb	22-Feb	24-Feb	11-Mar	12-Mar	13-Mar	14-Mar	15-Mar	16-Mar
SS	Mean	0.0b	0.0b	0.0a	0.5a	0.0a	4.4a	4.4a	3.9a	9.5a	3.2a
	CV				127.6		34.0	80.3	119.7	81.9	141.4
SF	Mean	0.0b	0.0b	0.0a	0.3a	0.6a	7.4a	0.9ab	0.2ab	1.9b	0.0a
	CV				173.2	88.2	10.3	173.2	173.2	173.2	
NS	Mean	18.0a	26.6a	7.5a	0.0a	21.0a	20.2a	0.3b	0.0b	0.0b	0.0a
	CV	83.3	50.3	134.8		62.5	107.7	173.2			
NF	Mean	14.7a	0.0b	4.2a	0.0a	23.0a	16.2a	0.0b	0.0b	0.8b	0.0a
	CV	87.7		107.9		91.1	90.1			112.5	

* - missing coefficients of variation indicate zero runoff from slope position or data obtained from only one frame.

- means on a given date with same letter not significantly different at (p=0.05).

SS - south slope (north-facing) 13% slope gradient. NS - north slope (south-facing) 13% slope gradient.

SF - south slope (north-facing) 5% slope gradient. NF - north slope (south-facing) 5% slope gradient.

Table 5.7. Average soil temperature (°C) for slope positions within the Sandy Subsoil Watershed during snowcover periods 1993 and 1994.

	Depth (cm)	11-Nov	20-Nov	13-Dec	6-Feb	27-Feb	2-Mar	3-Mar*	4-Mar	5-Mar	6-Mar	9-Mar	13-Mar	15-Apr	12-Mar	13-Mar	26-Mar
		1992			1993										1994		
SNL	5	5.8a	-1.3a	-6.6a	-3.5a	-3.1a	-1.3a	-1.6a	-2.1a	-1.2ab	-1.1ab	-0.9a	-2.8a	4.5ab	-1.0a	-1.0a	-1.0b
SNU	5	6.3a	-1.5ab	-6.8a	-3.3a	-2.9a	-1.1a	-1.6a	-1.8a	-0.8a	-0.7a	-1.0a	-2.8a	4.8a	-1.0a	-1.0a	1.3a
SSL	5	4.1b	-1.6ab	-5.4b	-4.0b	-5.0b	-1.9b	-2.5b	-4.2b	-2.0bc	-1.5b	-1.3a	-3.9b	1.5c	-1.2a	-1.2a	-1.4b
SSU	5	5.6a	-1.7b	-5.6b	-3.3a	-4.5b	-1.4a	-2.0a	-3.6b	-1.6c	-1.3ab	-1.6a	-3.9b	3.2b	-1.2a	-1.1a	-1.3b
SNL	10	4.9a	-1.1a	-6.2a	-4.3a	-3.7a	-1.6a	-1.8a	-1.8a	-1.4a	-1.3a	-0.9a	-2.6a	3.9a	-1.0a	-1.0a	-1.1a
SNU	10	5.0a	-1.2a	-6.3a	-4.2a	-3.5a	-1.5a	-1.7a	-1.6a	-1.0a	-1.3a	-0.9a	-2.7a	3.9a	-1.1a	-1.2ab	-0.5a
SSL	10	3.6c	-1.4a	-5.1b	-4.4a	-5.1b	-2.1b	-2.7b	-2.7b	-2.1b	-1.6b	-1.7ab	-3.7b	1.2b	-1.3a	-1.2ab	-1.4a
SSU	10	4.1b	-1.3a	-5.2b	-4.4a	-5.0b	-2.0b	-2.7b	-3.2b	-2.0b	-1.8b	-2.0b	-4.0b	1.5b	-1.2a	-1.3b	-1.5a
SNL	20	4.6a	-0.3a	-5.4a	-4.9a	-4.2a	-2.0a	-2.1a	-2.0a	-1.4a	-1.6a	-1.4a	-2.1a	3.7a	-1.2a	-1.1a	-1.0a
SNU	20	4.4a	-0.4ab	-5.2ab	-4.7a	-4.1a	-2.1a	-2.0a	-1.9a	-1.5a	-1.5a	-1.1a	-1.9a	3.8a	-0.9a	-1.4b	-1.1a
SSL	20	3.5b	-0.8b	-4.5b	-4.9a	-5.5b	-2.7b	-3.3b	-3.7c	-2.6b	-2.2b	-1.3a	-3.3b	0.1b	-1.6a	-1.6b	-1.6b
SSU	20	3.5b	-0.7b	-4.5b	-5.1a	-5.2b	-2.6b	-3.1b	-3.3b	-2.5b	-2.1b	-2.0a	-3.4b	0.9b	-1.8a	-1.5b	-1.6b
SNL	40	5.2	1.5	-3.1	-3.5	-4.1	-2.4	-2.2	-2.1	-2.2	-1.8	-0.6	-1.3	3.5	-1.5	-1.4	-0.8
SNU	40	5.3	1.4	-2.6	-3.2	-4.1	-2.6	-2.3	-2.1	-2.2	-1.8	-1.4	-1.3	2.6	-1.5	-1.4	-1.0
SSL	40	3.6	0.4	-2.8	-4.1	-5.0	-3.0	-3.2	-3.1	-2.9	-2.4	-1.3	-2.3	-0.3	-1.8	-1.4	-1.5
SSU	40	3.6	-0.2	-3.5	-4.5	-5.5	-3.2	-3.1	-3.9	-3.0	-2.7	-3.5	-2.3	1.0	-1.8	-1.6	-1.6

* - Hillslopes are clear of snow and runoff is finished. Snow commenced again after March 10, 1993.
- Means at a given depth or a given date with the same letter are not significantly different ($p<0.05$).
- Note: No statistical analysis was performed for 40 cm depth (no replicates).

SSL - south slope (north-facing) lower slope position.
SSU - south slope (north-facing) upper slope position.
SNL - north slope (south-facing) lower slope position.
SNU - north slope (south-facing) upper slope position.

Table 5.8. Average soil temperature (°C) for slope positions within the West Watershed during snowcover periods 1993 and 1994.

	Depths	11-Nov	20-Nov	13-Dec	6-Feb	27-Feb	2-Mar	3-Mar	4-Mar	5-Mar	6-Mar	9-Mar	13-Mar	13-Mar	25-Mar	26-Mar
		1992			1993									1994		
WNF	5	5.7	-1.8	-6.0	-2.2	-4.6	-	-1.2	-1.5	-1.1	-1.1	-1.0	-3.2	-1.0	-1.6	-1.4
WNS	5	7.0	-1.7	-6.8	-2.4	-4.3	-1.2	-1.2	-1.2	-1.0	-1.0	-1.0	-1.8	-1.2	-1.5	-1.4
WSF	5	5.2	-1.8	-5.9	-3.4	-5.2	-2.6	-2.8	-2.2	-1.8	-1.3	-1.8	-3.1	-1.2	-1.3	-1.2
WSS	5	4.7	-2.4	-5.8	-4.5	-6.0	-2.6	-2.7	-2.2	-2.1	-1.2	-1.0	-3.2	-1.2	-1.5	-1.4
WNF	10	4.7	-0.8	-5.2	-5.0	-4.6	-	-1.1	-1.6	-1.0	-1.3	-1.1	-2.6	-1.4	-1.6	-1.4
WNS	10	5.2	-0.5	-6.8	-3.7	-4.5	-1.8	-1.6	-1.5	-1.2	-1.3	-1.2	-1.8	-1.4	-1.6	-1.4
WSF	10	4.7	-1.6	-5.7	-3.8	-5.2	-2.6	-3.0	-2.2	-2.6	-1.4	-1.9	-3.1	-1.2	-1.4	-1.2
WSS	10	3.4	-1.8	-5.0	-5.0	-6.0	-2.8	-3.2	-2.9	-1.8	-1.8	-1.5	-2.9	-1.4	-1.8	-1.7
WNF	20	4.3	0.4	-3.5	-3.9	-4.5	-	-1.5	-2.3	-1.5	-1.6	-1.4	-2.0	-1.4	-1.5	-1.4
WNS	20	4.7	0.5	-6.0	-3.9	-4.5	-2.2	-2.1	-1.9	-1.7	-1.8	-1.5	-1.4	-1.5	-1.5	-1.4
WSF	20	3.5	-0.8	-5.0	-4.3	-5.2	-2.9	-3.2	-2.6	-2.9	-1.8	-2.7	-2.6	-1.5	-1.5	-1.4
WSS	20	2.9	-1.0	-3.6	-5.3	-6.0	-3.0	-3.6	-3.4	-2.2	-2.3	-1.9	-2.6	-1.7	-1.9	-1.7
WNF	40	2.2	2.0	-1.3	-3.1	-3.6	-	-2.0	-2.0	-2.0	-1.8	-1.7	-1.6	-1.1	-1.1	-1.0
WNS	40	5.0	0.7	-2.6	-3.7	-4.3	-2.2	-2.0	-1.9	-1.8	-1.6	-1.4	-1.2	-1.3	-1.3	-1.2
WSF	40	4.0	1.0	-2.6	-3.2	-5.2	-2.9	-2.9	-2.9	-2.6	-2.6	0.4	-2.2	-1.5	-1.5	-1.4
WSS	40	4.0	-1.5	-2.9	-3.4	-4.5	-3.0	-2.8	-2.9	-2.2	-2.6	-0.3	-1.8	-1.4	-1.3	-1.3

Note: Only one nest per slope position therefore no statistical analysis performed.

WSS - south slope (north-facing) 13% slope gradient.

WSF - south slope (north-facing) 5% slope gradient.

WNS - north slope (south-facing) 13% slope gradient.

WNF - north slope (south-facing) 5% slope gradient.

Table 5.9. Percentage of pre-melt snow-water that evaporated during 1993 and 1994 snowmelt.

	Number of Microframes*	Mean (%)	Standard Deviation (%)
Sandy Subsoil Watershed			
North-facing	6	38	22
South-facing	6	47	19
West Watershed			
North-facing	4	28	14
South-facing	3	43	9

* - Mass balance calculations were possible (no evidence of deep percolation).

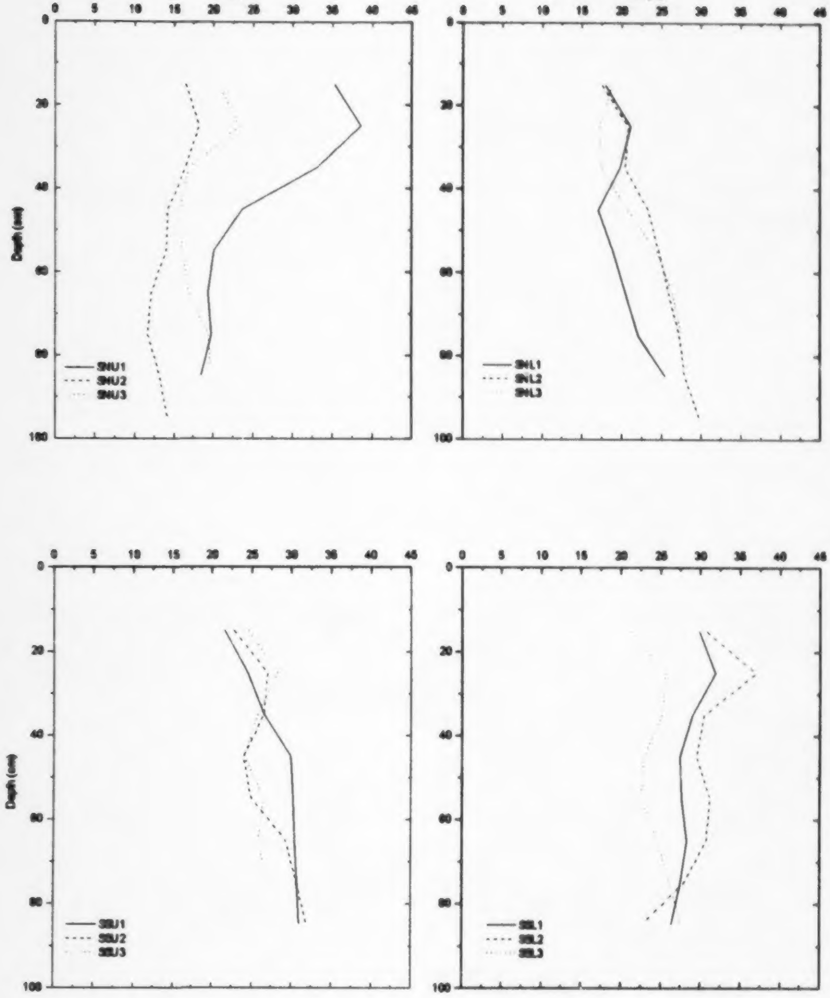

Figure 5.1. Pre-winter (November 16, 1992) soil moisture profiles for hillslope frames within the Sandy Subsoil Watershed.

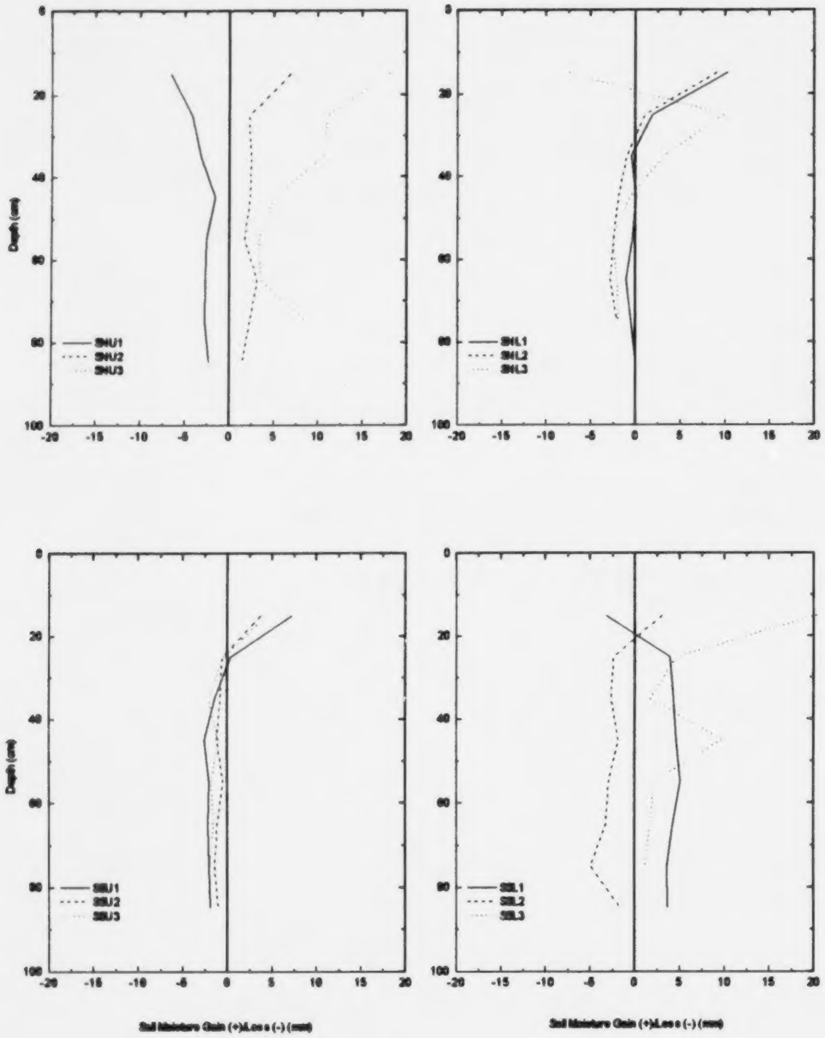

Figure 5.2. Soil moisture gain or loss at depth for over-winter, 1992-1993 for frames within the Sandy Subsoil Watershed.

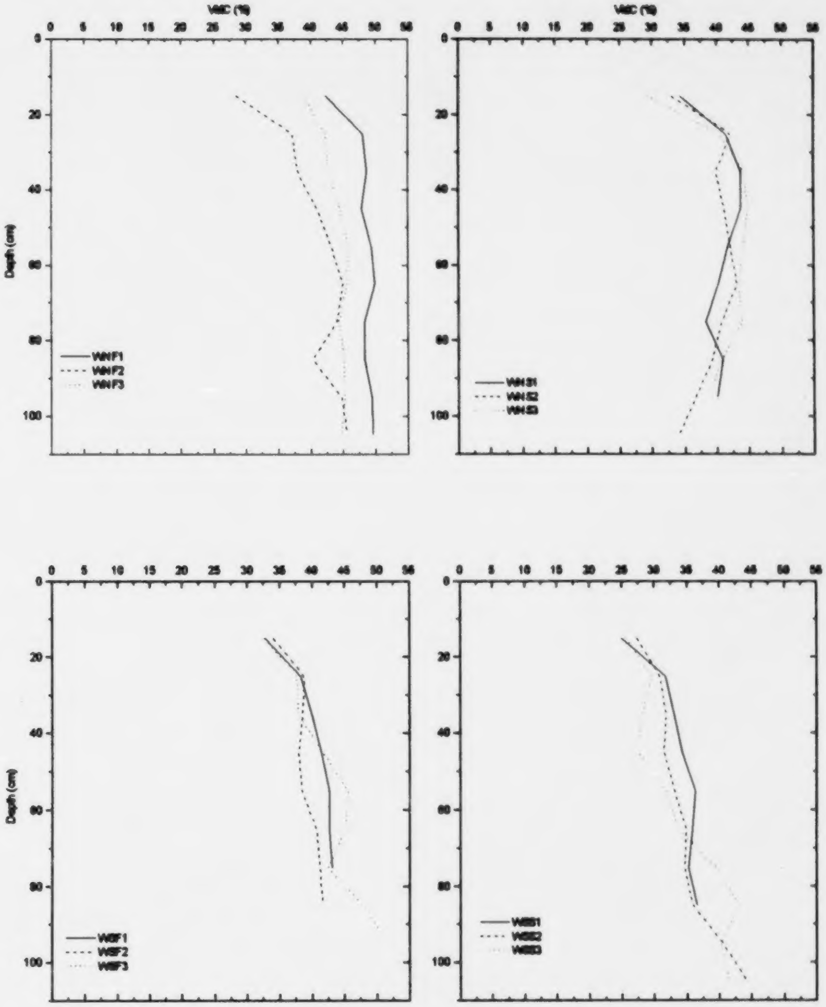

Figure 5.3. Pre-winter (November 16, 1992) soil moisture profiles for hillslope frames within the West Watershed.

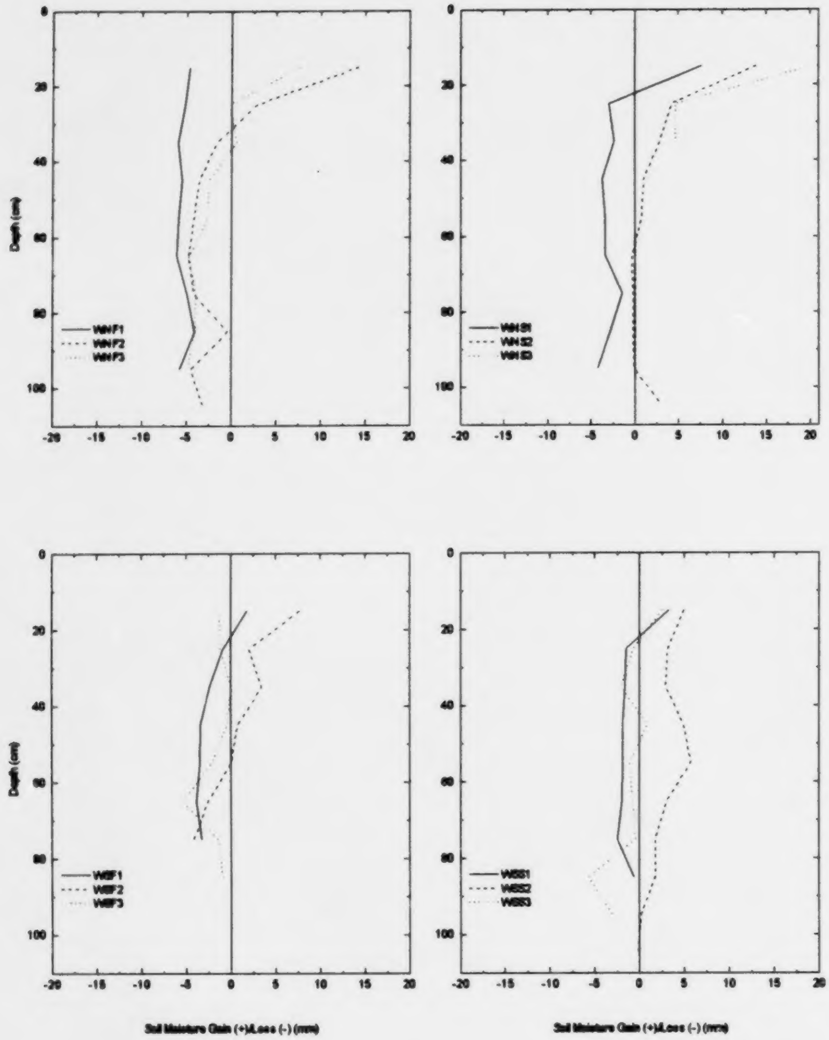

Figure 5.4. Soil moisture gain or loss at depth for over-winter, 1992-1993 for frames within the West Watershed.

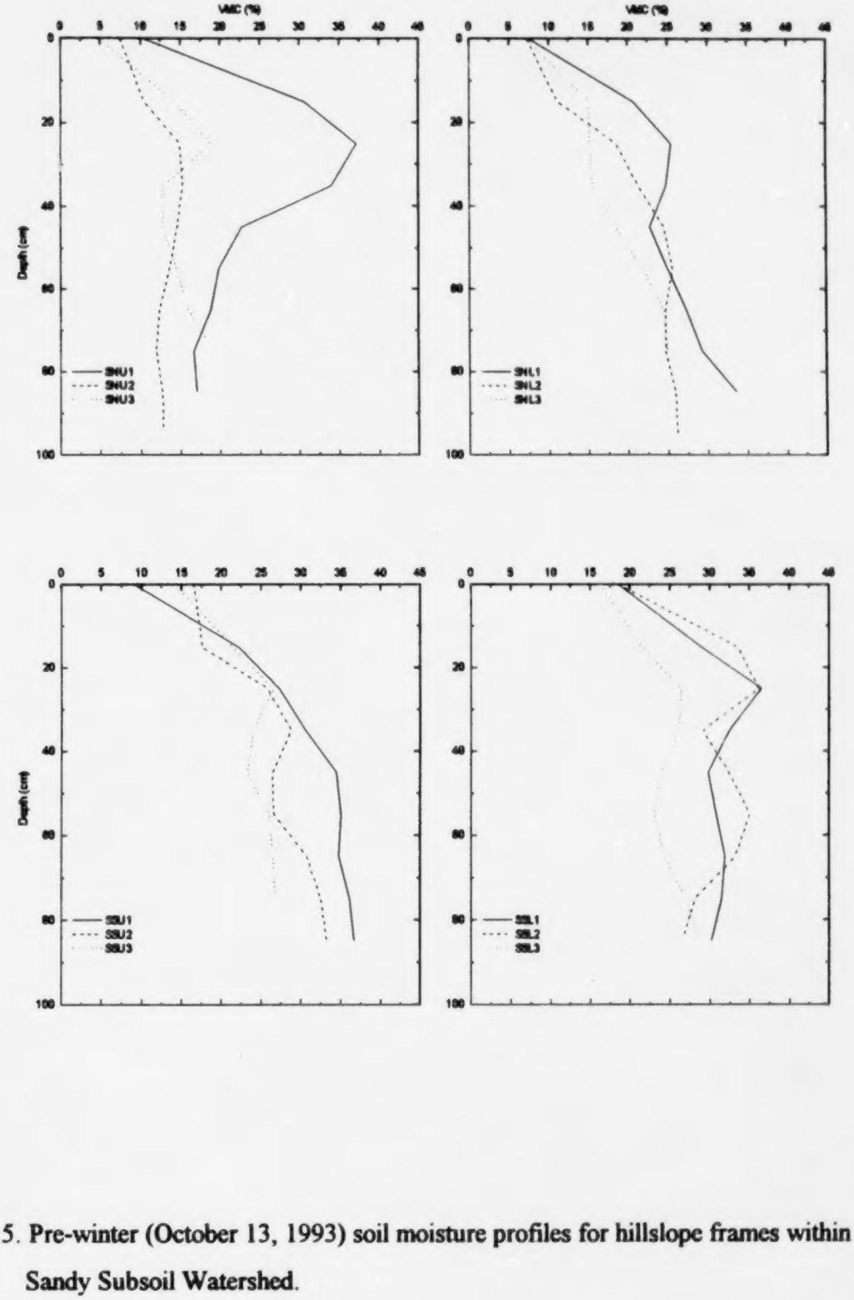

Figure 5.5. Pre-winter (October 13, 1993) soil moisture profiles for hillslope frames within the Sandy Subsoil Watershed.

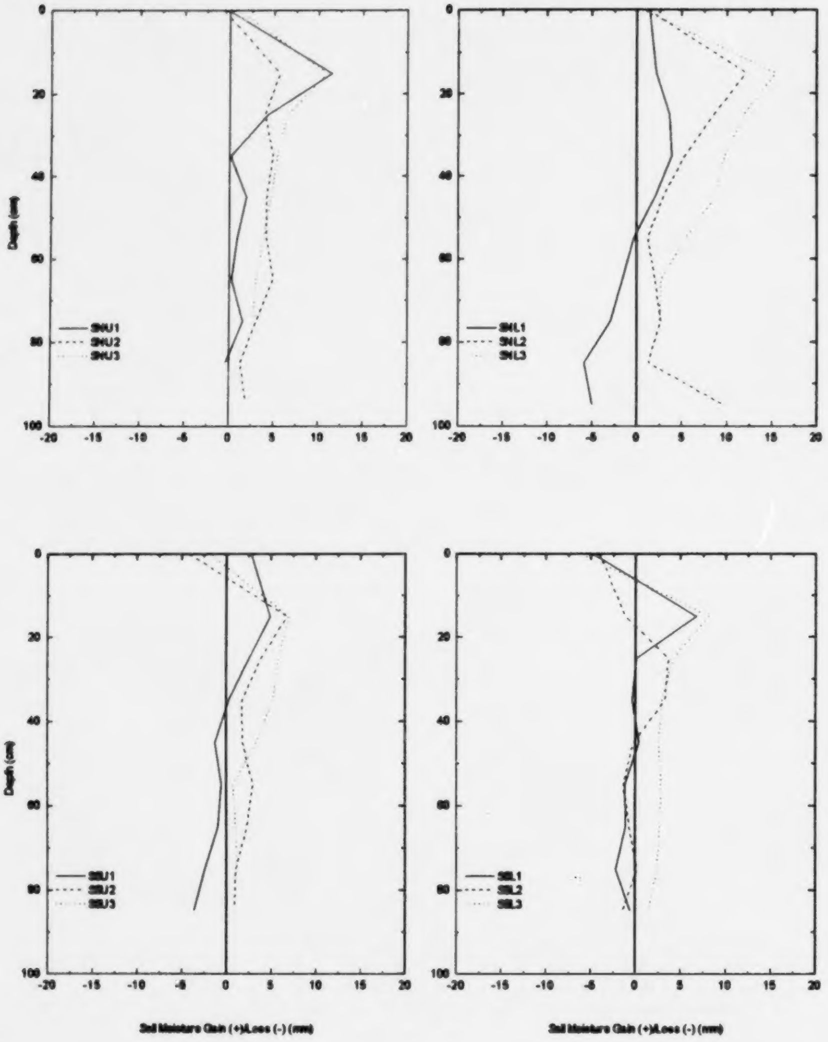

Figure 5.6. Soil moisture gain or loss at depth for over-winter, 1993-1994 for frames within the Sandy Subsoil Watershed.

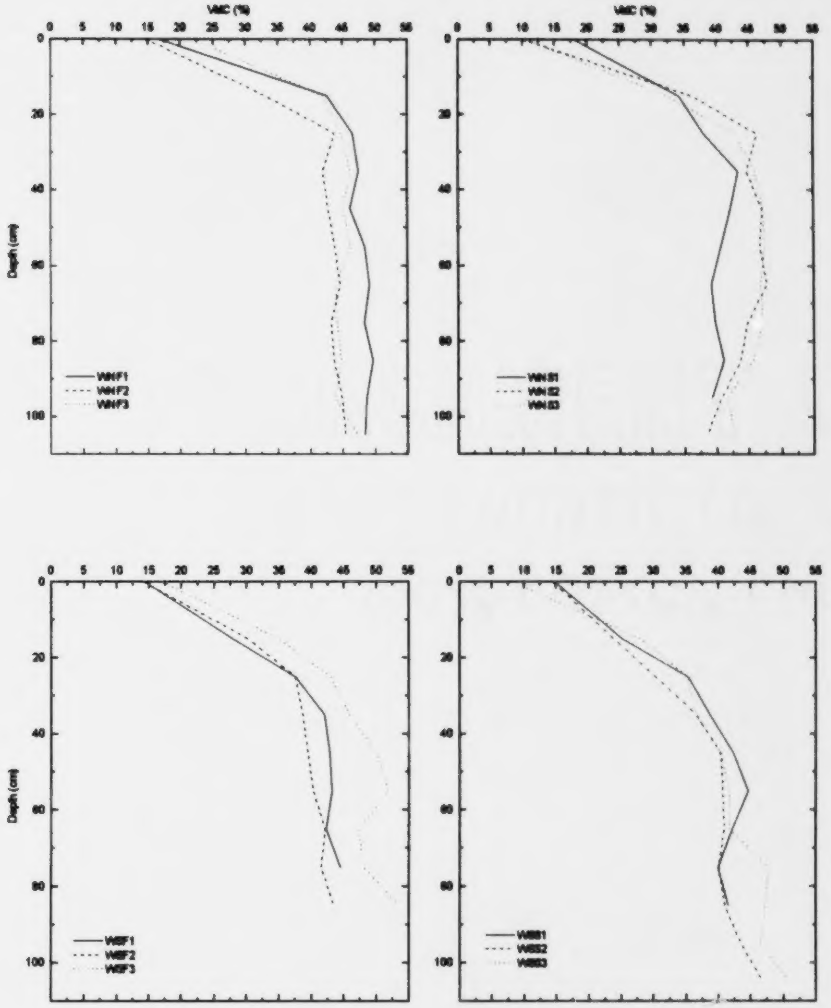

Figure 5.7. Pre-winter (October 13,1993) soil moisture profiles for hillslope frames within the West Watershed.

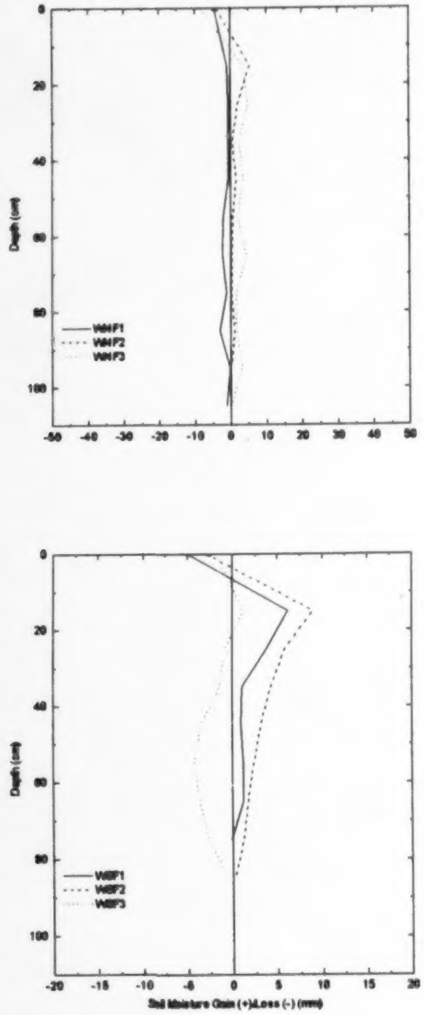

Figure 5.8. Soil moisture gain or loss at depth for over-winter, 1993-1994 for frames within the West Watershed.

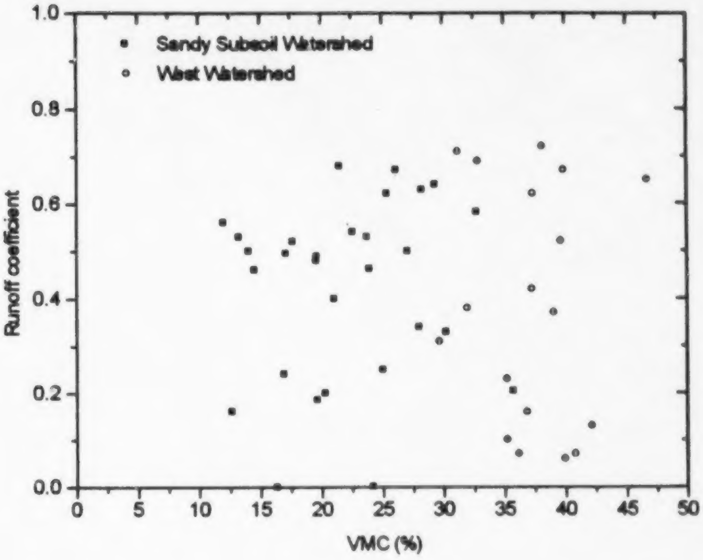

Figure 5.9. Frame runoff coefficient (snowmelt 1993 and 1994) vs pre-winter (November 16,1992 and October 13,1994) VMC (%) for both watersheds.

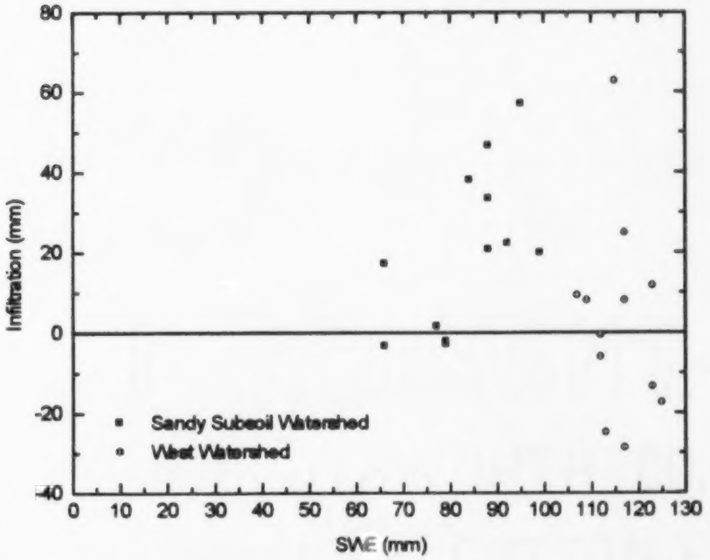

Figure 5.10. Relationship between snow-water equivalent and infiltration for both watersheds in 1994.

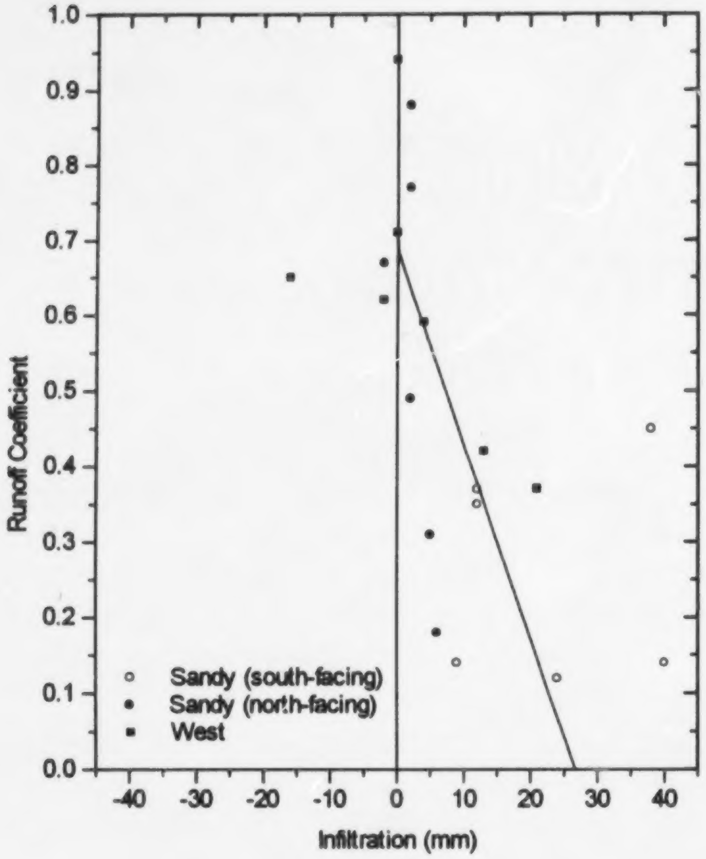

Figure 5.11. Relationship between runoff coefficient and infiltration.

Table 5.10. Microframe runoff (mm) during the 1992-1993 snow period for the Sandy Subsoil Watershed.

	13-Dec	27-Feb	1-Mar	2-Mar	20-Mar	22-Mar
SSL1	0.5	0.0	15.8	0.0	5.5	0.0
SSL2	18.5	0.0	25.8	3.5	15.8	1.6
SSL3	3.7	0.0	-	1.6	24.4	0.0
L Mean	7.6±5.5	0	20.8±5.0	1.7±1.0	15.2±5.4	0.5±0.5
SSU1	3.0	0.0	0.0	0.1	11.8	0.3
SSU2	25.3	18.0	13.3	0.0	2.0	0.7
SSU3	20.9	5.0	18.2	1.0	24.4	0.6
U Mean	16.4±6.8	7.7±5.4	10.5±5.4	0.4±0.3	12.7±6.5	0.5±0.1
Aspect Mean	12.0±4.4	3.9±2.9	15.7±4.2	1.1±0.6	14.0±3.8	0.5±0.2
SNL1	0.0	11.6	12.9	0.1	0.0	0.0
SNL2	0.0	2.3	7.9	0.0	0.0	0.0
SNL3	0.0	-	-	-	0.0	0.0
L Mean	0.0	7.0±4.7	10.4±2.5	0.0	0.0	0.0
SNU1	0.0	1.9	8.0	0.0	0.0	0.0
SNU2	0.0	21.2	-	0.1	0.0	0.0
SNU3	0.0	2.4	6.3	0.0	0.0	0.0
U Mean	0.0	8.5±6.4	7.2±0.9	0.0	0.0	0.0
Aspect Mean	0.0	7.8±3.8	8.8±1.4	0.0	0.0	0.0

Missing values are a result of leakage into collection bucket from outside the frame.

Means followed by standard error.

SSU - south slope (north-facing) upper slope position.

SSL - south slope (north-facing) lower slope position.

SNL - north slope (south-facing) lower slope position.

SNU - north slope (south-facing) upper slope position.

Table 5.11. Microframe runoff (mm) during the 1992-1993 snow period for West Watershed.

	13-Dec	27-Feb	28-Feb	1-Mar	2-Mar	3-Mar	4-Mar	5-Mar	6-Mar	7-Mar	20-Mar	21-Mar	22-Mar	23-Mar
WSS1	1.1	0.0	0.0	13.1	21.5	7.4	2.5	4.3	8.1	5.5	1.4	9.6	6.6	0.2
WSS2	0.0	0.0	0.0	13.2	21.3	9.2	3.2	8.6	12.9	3.6	1.8	16.3	7.2	0.4
WSS3	0.0	0.0	5.0	10.9	5.0	1.3	1.5	2.4	15.2	3.8	1.1	21.3	24.5	0.0
S Mean	0.4±0.4	0.0	1.7±1.7	12.4±0.8	15.9±5.5	6.0±2.4	2.4±0.5	5.1±1.8	12.1±2.1	4.3±0.6	1.4±0.2	15.7±3.4	12.8±5.9	0.2±0.1
WSF1	0.0	0.0	6.0	28.4	13.3	5.6	6.1	3.3	3.9	0.0	14.4	9.1	0.2	0.0
WSF2	0.0	0.0	0.0	22.4	1.1	3.2	5.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0
WSF3	0.0	0.0	4.0	21.2	12.0	5.0	0.5	0.0	0.0	0.0	5.7	0.0	0.0	0.0
F Mean	0.0	0.0	3.3±1.8	24.0±2.2	8.8±3.9	4.6±0.7	4.1±1.8	1.1±1.1	1.3±1.3	0.0	6.7±4.2	3.0±3.0	0.1±0.1	0.0
Aspect Mean	0.2±0.2	0.0	2.5±1.1	18.2±2.8	12.4±3.4	5.3±1.2	3.3±0.9	3.1±1.3	6.7±2.6	2.2±1.0	4.1±2.2	9.4±3.5	6.4±3.9	0.1±0.1
WNS1	0.0	-	-	-	-	-	-	-	-	-	-	-	-	-
WNS2	0.0	2.6	5.1	13.0	1.3	0.0	0.0	0.0	0.0	0.0	5.6	0.0	0.2	0.0
WNS3	0.0	0.0	5.0	12.5	0.0	0.0	0.0	0.0	0.0	0.0	2.2	0.0	0.0	0.0
S Mean	0.0	1.3±1.3	5.1±0.1	12.8±0.3	0.7±0.7	0.0	0.0	0.0	0.0	0.0	3.9±1.7	0.0	0.1±0.1	0.0
WNF1	0.0	1.1	7.0	20.1	10.3	0.0	0.0	0.0	0.0	0.0	4.4	0.0	0.0	0.0
WNF2	0.0	-	-	-	-	-	-	-	-	-	-	-	-	-
WNF3	0.0	-	-	-	-	-	-	-	-	-	-	-	-	-
F Mean	0.0	1.1	7.0	20.1	10.3	0.0	0.0	0.0	0.0	0.0	4.4	0.0	0.0	0.0
Aspect Mean	0.0	1.2±0.8	5.7±0.7	15.2±2.5	3.9±3.2	0.0	0.0	0.0	0.0	0.0	4.1±1.0	0.0	0.1±0.1	0.0

Missing values are a result of freezing of collection system during mid-winter melts.

Means followed by standard error.

SS = south slope (north-facing) steep slope.
NS = north slope (south-facing) steep slope.
SF = south slope (north-facing) flat slope.
NF = north slope (south-facing) flat slope.

Table 5.12. Microframe runoff (mm) during the 1993-1994 snow period for the Sandy Subsoil Watershed.

	26-Dec	11-Mar	12-Mar	13-Mar	14-Mar	15-Mar	16-Mar	18-Mar	25-Mar
SSL1	0.3	5.7	3.5	18.0	10.8	27.7	5.2	2.7	0.0
SSL2	24.1	-	-	-	16.0	4.2	23.6	-	6.9
SSL3	2.4	6.0	4.0	21.3	13.6	-	-	-	2.2
L Mean	8.9±7.6	5.9±0.2	3.8±0.3	19.7±1.7	13.5±1.5	16.0±11.8	14.4±9.2	2.7	3.0±2.0
SSU1	8.8	3.9	2.6	34.4	28.0	15.0	8.3	1.3	0.0
SSU2	20.4	4.5	2.8	35.3	26.7	-	-	-	1.8
SSU3	18.1	5.1	4.5	19.7	16.6	-	14.0	2.7	0.0
U Mean	15.8±3.5	4.5±0.3	3.3±0.6	29.8±5.1	23.8±3.6	15.0	11.2±2.9	2.0±0.7	0.6±0.6
Aspect Mean	12.4±4.1	5.0±0.4	3.5±0.4	25.7±3.8	18.6±2.9	15.6±6.8	12.8±4.0	2.2±0.7	1.8±1.1
SNL1	3.4	11.8	0.5	0.0	0.3	25.3	0.0	0.0	0.0
SNL2	1.4	-	13.0	-	-	27.5	0.0	0.0	0.0
SNL3	3.0	13.7	12.6	22.7	35.8	0.0	0.0	0.0	0.0
L Mean	2.6±0.6	12.8±1.0	8.7±4.1	11.4±11.4	18.1±17.8	17.6±8.8	0.0	0.0	0.0
SNU1	3.5	-	-	-	-	31.0	3.0	0.0	0.0
SNU2	3.1	16.8	20.5	-	27.3	11.4	0.3	0.0	0.0
SNU3	0.3	12.2	0.2	0.0	0.7	0.0	0.0	0.0	0.0
U Mean	2.3±1.0	14.5±2.3	10.4±10.2	0.0	14.0±13.3	14.1±9.1	1.1±1.0	0.0	0.0
Aspect Mean	2.5±0.5	13.6±1.1	9.4±3.9	7.6±7.6	16.0±9.1	15.9±5.7	0.6±0.5	0.0	0.0

Missing values are a result of ice-jamming behind frame during melt period.

Table 5.13. Microframe runoff (mm) during the 1993-1994 snow period for West Watershed.

	26-Dec	13-Mar	14-Mar	15-Mar	16-Mar	18-Mar	25-Mar	26-Mar	27-Mar	28-Mar	30-Mar
WSS1	3.2	8.6	4.3	2.7	2.2	3.1	30.3	29.2	5.8	1.1	0.6
WSS2	8.0	4.4	4.6	3.9	1.9	3.1	10.2	46.9	26.8	19.0	0.8
WSS3	0.6	5.8	4.1	3.3	1.8	2.7	44.3	41.8	-	-	17.2
S Mean	3.9±2.2	6.3±1.2	4.3±0.1	3.3±0.3	2.0±0.1	3.0±0.1	28.3±9.9	39.3±5.3	16.3±10.5	10.1±9.0	6.2±5.5
WSF1	7.7	10.3	5.6	4.7	1.9	0.4	11.2	-	30.7	6.4	2.1
WSF2	0.0	0.0	0.0	0.0	0.0	0.0	24.9	2.6	16.9	-	0.0
WSF3	2.1	9.1	0.0	5.1	1.5	2.6	3.1	4.5	40.5	-	24
F Mean	3.3±2.3	6.5±3.3	1.9±1.9	3.3±1.6	1.1±0.6	1.0±0.8	13.1±6.4	3.6±1.0	29.4±6.9	6.4	8.7±7.7
Aspect Mean	3.6±1.4	6.4±1.6	3.1±1.0	3.3±0.7	1.6±0.3	2.0±0.6	20.7±6.3	25.0±9.2	24.1±5.9	8.8±5.3	7.5±4.3
WNS1	2.6	-	-	-	-	11.8	-	-	0.0	0.0	0.0
WNS2	0.4	18.6	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0
WNS3	-	-	-	-	-	-	-	-	-	-	-
S Mean	1.0±0.8	9.3±9.3	0.0	0.0	0.1±0.1	3.9±3.9	0.0	0.0	0.0	0.0	0.0
WNF1	5.2	19.6	0.0	11.8	0.0	-	28.3	14.8	0.0	0.0	0.0
WNF2	0.0	13.9	0.0	0.0	0.0	4.3	5.0	1.4	0.0	0.0	0.0
WNF3	0.0	7.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
F Mean	1.7±1.7	13.6±3.6	0.0	3.9±3.9	0.0	2.2±2.2	11.1±8.7	5.4±4.7	0.0	0.0	0.0
Aspect Mean	1.4±0.9	11.9±3.7	0.0	2.4±2.4	0.0	3.2±2.3	6.7±5.5	3.2±2.9	0.0	0.0	0.0

Missing values are a result of ice-jamming behind frame during melt period. WNS3 had a mouse-hole in middle of frame discovered in spring.

Table 5.14. Microframe runoff (mm) during the 1994-1995 snow period for the Sandy Subsoil Watershed.

	1-Feb	9-Feb	21-Feb	22-Feb	24-Feb	11-Mar	12-Mar	13-Mar	14-Mar	15-Mar	16-Mar
SSL1	0.7	1.5	13.2	19.3	2.0	6.9	12.0	1.0	0.7	8.2	3.4
SSL2	0.0	1.5	3.5	3.2	2.2	0.9	6.2	7.6	22.8	23.2	10.2
SSL3	1.0	3.0	20.0	32.0a	4.0	4.5	25.7a	7.6	4.0	37.0a	10.0
L Mean	0.6±0.3	2.0±0.5	12.2±4.8	11.3±8.1	2.7±0.6	4.1±1.7	9.1±2.9	5.4±2.2	9.2±6.9	15.7±7.5	7.9±2.2
SSU1	4.3	3.1	10.0	14.0	1.1	9.4	12.6	1.1	0.5	0.6	0.0
SSU2	1.0	1.6	6.0	7.7	0.5	1.7	7.8	3.0	4.2	6.5	2.5
SSU3	2.8	1.5	8.0	4.0	0.8	4.0	6.5	0.0	0.0	0.0	0.0
U Mean	2.7±1.0	2.1±0.5	8.0±1.2	8.6±2.9	0.8±0.2	5.0±2.3	9.0±1.9	1.4±0.9	1.6±1.3	2.4±2.1	0.8±0.8
Aspect Mean	1.6±0.7	2.0±0.3	10.1±2.4	9.6±3.1	1.8±0.5	4.6±1.3	9.0±1.4	3.4±1.4	5.4±3.7	7.7±4.2	4.4±1.9
SNL1	9.1	10.1	13.2	7.2	0.0	14.5	1.0	0.0	0.0	0.0	0.0
SNL2	6.1	5.0	4.9	4.0	0.0	4.7	0.7	0.0	0.0	0.0	0.0
SNL3	34.6	16.0	24.1	1.0	0.0	16.0	0.0	0.0	0.0	0.0	0.0
L Mean	16.6±9.0	10.4±3.2	14.1±5.6	4.1±1.8	0.0	11.7±3.5	0.6±0.3	0.0	0.0	0.0	0.0
SNU1	8.0	10.0	8.0	5.7	0.0	19.2	0.3	0.0	0.0	0.0	0.0
SNU2	16.0	50.0a	28.0a	21.0	0.0	48.0a	28.6a	0.0	0.0	0.0	0.0
SNU3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
U Mean	8.0±4.6	5.0±5.0	4.0±4.0	8.9±6.3	0.0	9.6±9.6	0.2±0.2	0.0	0.0	0.0	0.0
Aspect Mean	12.3±4.9	8.2±2.7	10.0±4.1	6.5±3.1	0.0	10.9±3.6	0.4±0.2	0.0	0.0	0.0	0.0

[a] - possible leakage into collection system (Runoff coefficients greater than 1.0).
Means followed by standard error.

Table 5.15. Microframe runoff (mm) during the 1994-1995 snow period for West Watershed.

	9-Feb	21-Feb	22-Feb	24-Feb	11-Mar	12-Mar	13-Mar	14-Mar	15-Mar	16-Mar
WSS1	0.0	0.0	0.0	1.3	0.0	6.0	1.7	0.6	4.0	0.0
WSS2	0.0	0.0	0.0	0.0	0.0	3.1	8.4	54.0a	26.0a	22.0a
WSS3	0.0	0.0	0.0	0.3	0.0	4.0	3.1	7.2	15.0	6.3
S Mean	0.0	0.0	0.0	0.5±0.4	0.0	4.4±0.9	4.4±2.0	3.9±3.3	9.5±5.5	3.2±3.2
WSF1	0.0	0.0	0.0	1.0	1.0	7.9	0.0	0.0	0.0	0.0
WSF2	0.0	0.0	0.0	0.0	0.0	6.5	2.6	0.6	0.0	0.0
WSF3	0.0	0.0	0.0	0.0	0.8	7.7	0.0	0.0	5.8	0.0
F Mean	0.0	0.0	0.0	0.3±0.3	0.6±0.3	7.4±0.4	0.9±0.9	0.2±0.2	1.9±1.9	0.0
Aspect Mean	0.0	0.0	0.0	0.4±0.2	0.3±0.2	5.9±0.8	2.6±1.3	1.7±1.4	5.0±2.8	1.3±1.3
WNS1	3.0	17.1	3.5	0.0	19.0	43.3	1.0	0.0	0.0	0.0
WNS2	33.0	64.0[a]	19.0	0.0	35.0	17.4	0.0	0.0	0.0	0.0
WNS3	18.0	36.0	0.0	0.0	9.0	0.0	0.0	0.0	0.0	0.0
S Mean	18.0±10.4	26.6±18.8	7.5±5.8	0.0	21.0±7.6	20.2±12.6	0.3±0.3	0.0	0.0	0.0
WNF1	24.0	64.0[a]	9.0	0.0	28.0	28.4	0.0	0.0	1.7	0.0
WNF2	20.0	64.0[a]	3.6	0.0	41.0	20.3	0.0	0.0	0.6	0.0
WNF3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
F Mean	14.7±8.5	0.0	4.2±2.6	0.0	23.0±12.1	16.2±8.4	0.0	0.0	0.8±0.5	0.0
Aspect Mean	16.3±6.7	17.7±10.2	5.9±3.0	0.0	22.0±6.4	18.2±6.8	0.2±0.2	0.0	0.4±0.3	0.0

[a] - possible leakage into collection system.

6. SYNTHESIS

The hydrologic investigation described in part within this thesis has allowed me excellent opportunities to examine many components operating within the hydrologic cycle. It has been an excellent learning ground to discover the complexities of the processes operating within the land component of the hydrologic cycle; even within fairly small watersheds. The dynamic and unpredictable nature of the runoff process for both summer rainfall and spring snowmelt events has necessitated the development of some unique monitoring to capture the temporal links between rainfall/runoff during summer rainfall events and energy inputs/melt/runoff during spring snowmelt events. I have enjoyed the research immensely and hope my future career proves to be as exciting and intriguing as this research.

6.1. Runoff Process

Snowmelt runoff comprised the majority of runoff volume discharged from these two reclaimed watersheds during most years of "normal" or near normal snow accumulation and rainfall. Annual watershed runoff amounts for 1993 and 1994 were dominated by snowmelt runoff when snow accumulation was near long term normals for the area as reported from the AES Stony Plain Meteorological station.

Watershed runoff from snowmelt was assured even for years when snow-water equivalents were extremely low but hillslope or watershed runoff does not necessarily occur during periods of mid-winter melts. Much or all of the meltwater produced during mid-winter melts can infiltrate into the unsaturated soil or evaporate and no runoff results; particularly for the hillslopes within watersheds with south-facing aspects.

Watershed discharge during summer rainfall events occurred less certain than it did for snowmelt events. The frequency of watershed runoff in response to summer rainfall inputs within small watersheds with ephemeral drainage channels depended on the dominant processes occurring along the channel areas in addition to the supply of runoff coming from the hillslopes. Much of the hillslope overland flow can be retained within some watersheds if channel storage and channel transmission losses are high. Surface discharge will occur only during the most intense summer rainfall events that have long recurrence intervals (1:10 year or greater). This was the process operating within the Sandy Subsoil Watershed and watershed runoff occurred only twice during three years of monitoring in response to rainfall events with amount/duration return periods of greater than 10 years.

For other watersheds, surface discharge can occur in response to less intense summer rainfall events when soil moisture along the channel area remains high between rainfall inputs or saturates during the rainfall event. Infiltration is limited due to the saturated areas within the channel and any rainfall input to the channel area immediately becomes runoff. Within these watersheds the hillslopes do not necessarily provide the runoff to the channel but direct precipitation onto the saturated areas along the channel is the main source of the surface flow. The lack of uniform hillslope overland flow even during quite intense summer rainfall events and the frequency of watershed discharge during summer storms with return periods of 2 years likely indicates that saturation overland flow was the dominant flow path occurring within the West Watershed.

Dominant flow pathways can be different for seemingly simple watersheds when there are differences in soil texture, slope gradients and channel permeability. Different flow processes are not limited to heterogeneous catchments.

6.2. Runoff Magnitude

The highest instantaneous peak discharge recorded during the study occurred from the West Watershed in 1995 (79 L/s) during an intense summer rainfall event with a return period greater than 50 years. Antecedent soil moisture was high prior to this event and channel storage was full. Previously, the highest instantaneous peak discharge was 15 L/s. The highest snowmelt peak flow of 32 L/s occurred during the 1994 spring snowmelt from the West Watershed.

The highest instantaneous peak discharge from the Sandy Subsoil Watershed of 30 L/s occurred during snowmelt of 1994. The highest summer instantaneous peak discharge for this watershed of 20 L/s occurred in summer 1995. Differences in runoff volume and peak depend on the nature of the dominant flow pathways that operate within watersheds and generalizations about watershed hydrology must be made cautiously.

6.3. Runoff Coefficients

The dominance of snowmelt runoff in the annual water budget is highlighted when comparisions are made between seasonal runoff coefficients. Runoff coefficients for the Sandy Subsoil Watershed were higher for the snow season November to March (0.36 in 1994, 0.17 in 1995) than they were for the rainfall season April to September (0.01 in 1993, 0.00 in 1994 and 0.02 in 1995). Similarly runoff coefficients for the West Watershed were higher for the snow season (0.25 in 1993, 0.29 in 1994, and 0.15 in 1994) than for the rainfall season (0.01 in 1993, 0.00 in 1994, and 0.04 in 1995).

Hillslope runoff coefficients were generally greater than 0.05 for the Sandy Subsoil Watershed if the rainfall amount was greater than 25 mm and the product of the 5-min and 30-min intensities was greater than 100. Similarly, hillslope runoff coefficients were greater than 0.05 for the West Watershed if the rainfall amount was greater than 30 mm and the product of the 5-min and 30-min intensities was greater than 500.

Runoff coefficients for the Sandy Subsoil Watershed for summer rainfall events obtained from the hillslope microframes were consistently and substantially higher than the runoff coefficient obtained from runoff measured at the watershed outlet, and runoff from rainfall was much more frequent from the hillslope frames than it was from the watershed. Within the West Watershed, runoff coefficients for the hillslope frames were generally higher than the runoff coefficient at the watershed outlet. However, on one occasion, watershed runoff occurred without any hillslope runoff. Snowmelt hillslope frame runoff coefficients were also higher than the outlet snowmelt runoff coefficients. Hence, if the role of the channel in the generation or attenuation of overland flow is not considered, then the prediction of watershed runoff from hillslope microframes would likely be in error.

6.4. Influence of Aspect

Aspect is a very important factor when determining the timing and amount of snowmelt runoff, and the amount of runoff from summer rainfall events for small watersheds. Snowmelt runoff began from the south-facing slopes early into the melt and hence initial watershed runoff during snowmelt was predominantly from this aspect. Evaporation for this aspect was higher as a result of higher energy inputs, hence snowmelt runoff volume was less for the south-facing aspect than it was for the north-facing aspect. Snowmelt on the north-facing aspect commenced later, sustaining the duration of watershed snowmelt runoff.

Aspect was a major factor determining the amount of hillslope runoff from summer rainfall events within the Sandy Subsoil Watershed. Soil moisture was lower for the south-facing aspect; hence, unsaturated soil pore space was higher and initial infiltration would also be higher. The south-facing aspect yielded less runoff than the north-facing aspect within this watershed during every summer rainfall event during the three study years. Aspect was not as pronounced within the West Watershed, and did not have the same influence as it did for the Sandy Subsoil Watershed. Hillslope frames located within the suspected saturated area contributed the most runoff during 1995 summer rainfall events. This pattern was not evident for the previous two years, but in 1994, summer rainfall was minimal for all hillslope locations within the West Watershed.

6.5. Soil Moisture and Snowmelt

Soil profiles with high fall soil moisture generally had less snow-water infiltration and hence higher runoff. However, the relationship between soil moisture, infiltration and snow-water equivalent that was described by Granger et al. (1984) was not evident within these watersheds likely due to major mid-winter melts during the three years of monitoring. Midwinter melts increased the pre-winter soil moisture, changed the nature of the frozen soil surface to make it less permeable, altered the accumulated snow characteristics and contributed to partial filling of surface depressions. These alterations to the soil and snow made relationships drawn from pre-winter conditions difficult to apply.

Infiltration of melt-water occurred at soil temperatures that remained below 0 °C during the entire melt. Higher infiltration generally occurred at hillslope locations with lower soil moisture prior to winter, but soil surface characteristics such as macropores must also influence the amount of infiltration during snowmelt.

6.6. Runoff Quality

Runoff from these two well-vegetated reclaimed watersheds is low in total suspended solids, electrical conductivity, nitrate-nitrogen, ammonium and total phosphates and pH is near neutral. The water quality should continue to remain very good as long as the watersheds retain their dense vegetative cover and soil surface disturbance within the watersheds is minimal.

6.7. Future Research

Transference of the research results to non-disturbed areas should be possible in that the processes occurring within the reclaimed watersheds are processes that could occur within watersheds with similar topographic, vegetative and pedologic features. It would be desireable to establish a similar watershed study on agricultural and forested watersheds with similar topography and soils to the reclaimed watersheds to identify the dominant flow processes that occur within them.

Description of the channel area within small watersheds relating to saturated areas along its length or channel transmission losses is fundamental to understanding how the watershed responds to rainfall inputs. Detailed description of the channel and intensive monitoring of soil moisture, flow depth and flow amount along the channel area during rainfall events would aid in understanding what variables most influence the behavior of the channel during precipitation inputs.

A common complaint about many present computer models that can be used to predict watershed runoff is that they are very poor at predicting the timing and amount of snowmelt runoff. A detailed study to quantify the variability of energy inputs to a snowpack, snowmelt runoff, and snow-water infiltration occurring at numerous slope positions and aspects within a small watershed would help to improve the snowmelt modeling routines of many current runoff models.